Nucleosynthesis — the origin of the elements

We have seen that the $\oplus$ is composed of four major elements:

$$\boxed{Fe : Mg : Si : O \approx 1 : 1 : 1 : 3\tfrac{1}{2}}$$

why not, e.g. 100% uranium?

In this lecture we ask — why are these the dominant elements? — and where do the elements come from anyway?

~~As noted earlier the composition of the Sun is known from~~

At the risk of insulting you let me remind you what an element is.

Atoms are composed of protons, neutrons and electrons — the masses of these particles are well known — measured in atomic mass units ≡ amu (also called a Dalton)

$$1 \text{ amu} = \frac{1}{12} \text{ mass of } {}^{12}C \text{ atom}$$

$$= 1.67 \cdot 10^{-27} \text{ kg}$$

↑ most common carbon ~~oxygen~~ isotope

changed in 1960

TABLE 2-2

Simple Earth Model·Based on Cosmic Abundances

Oxides	Molecules	Molecular Weight	Grams	Weight Fraction
MgO	1.06	40	42.4	0.250
SiO_2	1.00	60	60.0	0.354
Al_2O_3	0.0425	102	4.35	0.026
CaO	0.0625	56	3.5	0.021
Na_2O	0.03	62	1.84	0.011
Fe_2O	0.45	128	57.6	0.339
Total			169.7	1.001

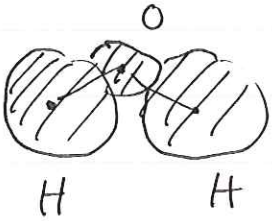
$$\oplus \approx MgO + SiO_2 + \frac{1}{2} Fe_2O$$

proton	1.00758 amu	+ charge
neutron	1.00897 amu	neutral
electron	$5.5 \cdot 10^{-4}$ amu	− charge

Structure of atom (sixth-grader's view)

protons & neutrons in <u>nucleus</u>

electrons in surrounding cloud



H_2O molecule

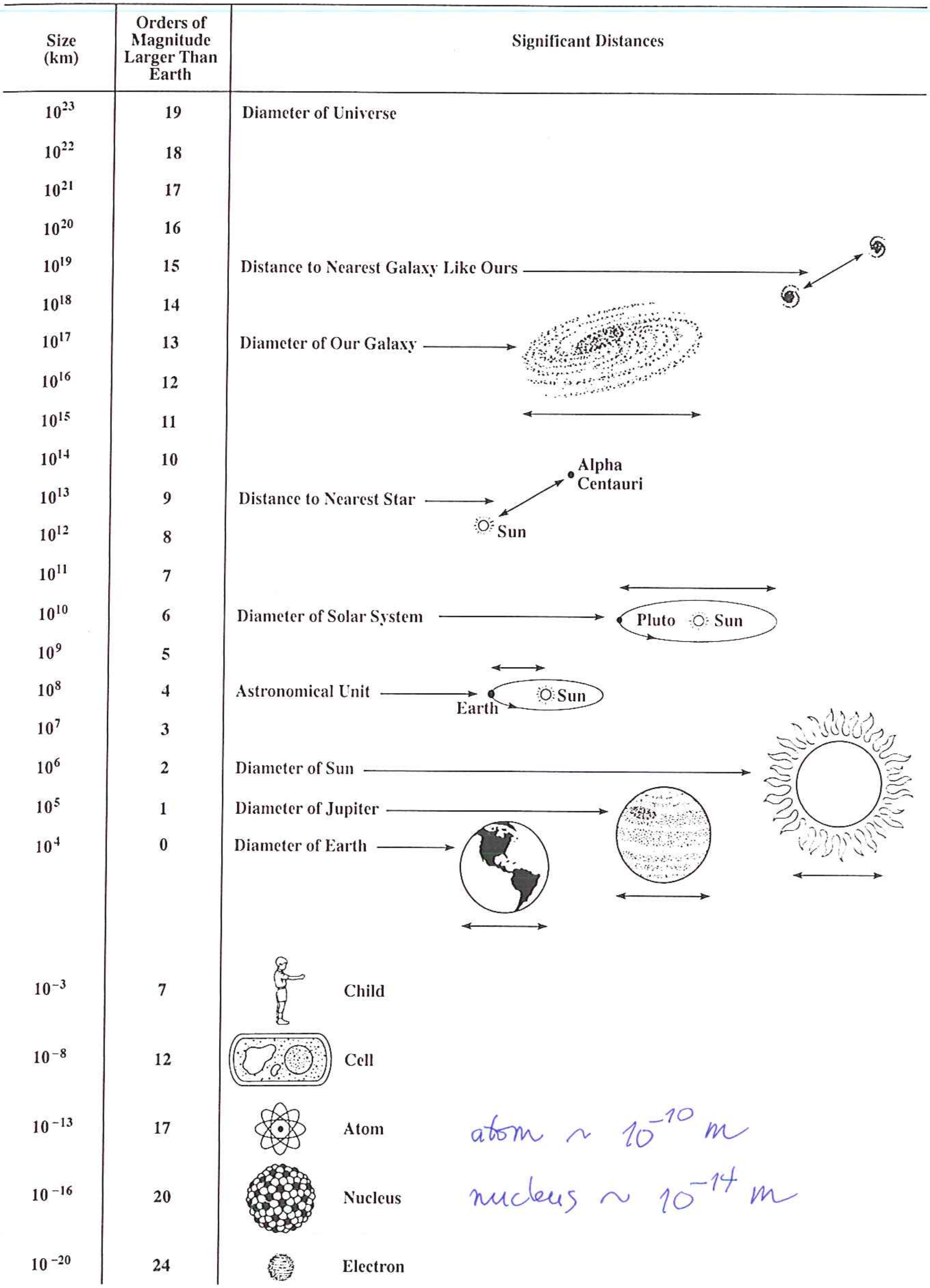
Z = # of protons (atomic number)
N = # of neutrons
A = Z + N = # of nucleons

Neutral atom — # electrons = # protons (to balance charge)

Typical sizes : atom : 10^{-10} m
nucleus : 10^{-14} m

← if atom size of classroom, nucleus size of head of a pin!

Electrons, weigh only 0.02–0.03% of atom, take up almost all the space.



Size (km)	Orders of Magnitude Larger Than Earth	Significant Distances
10^{23}	19	Diameter of Universe
10^{22}	18	
10^{21}	17	
10^{20}	16	
10^{19}	15	Distance to Nearest Galaxy Like Ours
10^{18}	14	
10^{17}	13	Diameter of Our Galaxy
10^{16}	12	
10^{15}	11	
10^{14}	10	
10^{13}	9	Distance to Nearest Star
10^{12}	8	
10^{11}	7	
10^{10}	6	Diameter of Solar System
10^{9}	5	
10^{8}	4	Astronomical Unit
10^{7}	3	
10^{6}	2	Diameter of Sun
10^{5}	1	Diameter of Jupiter
10^{4}	0	Diameter of Earth
10^{-3}	7	Child
10^{-8}	12	Cell
10^{-13}	17	Atom
10^{-16}	20	Nucleus
10^{-20}	24	Electron

atom ~ 10^{-10} m

nucleus ~ 10^{-14} m

Figure 2.1. Sizes of various objects over the enormous range that the natural world encompasses. From Robbins and Jeffreys (1988) by permission of John Wiley and Sons.

The density of matter (e.g. $\bar{\rho}_{\oplus} = 5500\ \mathrm{kg/m^3}$) is really the density of electrons.

The nuclei are incredibly small & dense "matter mostly empty space"

Density of ^{16}O nucleus:

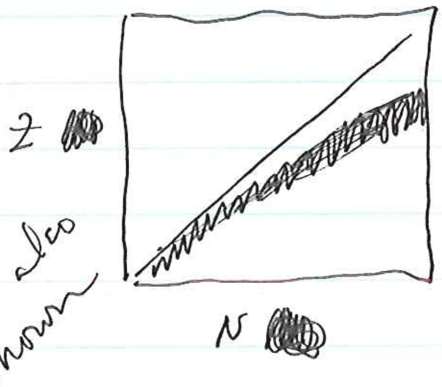
$$\rho \approx \frac{(16)(1.7\cdot 10^{-27}\ \mathrm{kg})}{\frac{4}{3}\pi\,(10^{-14}\ \mathrm{m})^3} \approx 6\cdot 10^{15}\ \mathrm{kg/m^3}$$

$$\boxed{\rho_{\text{nucleus}} \approx 10^{12}\ \bar{\rho}_{\oplus}}$$

density of nuclear matter — also of neutron stars

All elements have more than one isotope — number of neutrons in nucleus does not affect number of electrons ⟹ identical chemistry.

Table of nuclides: plot Z versus N



stable isotopes

on GE wall chart grey = stable; $\tau_{1/2}$ of unstable nuclides also shown

Show Fig. 2.2 Broecker and 2.13 closeups

Heaviest stable element bismuth Bi
$Z = 83$

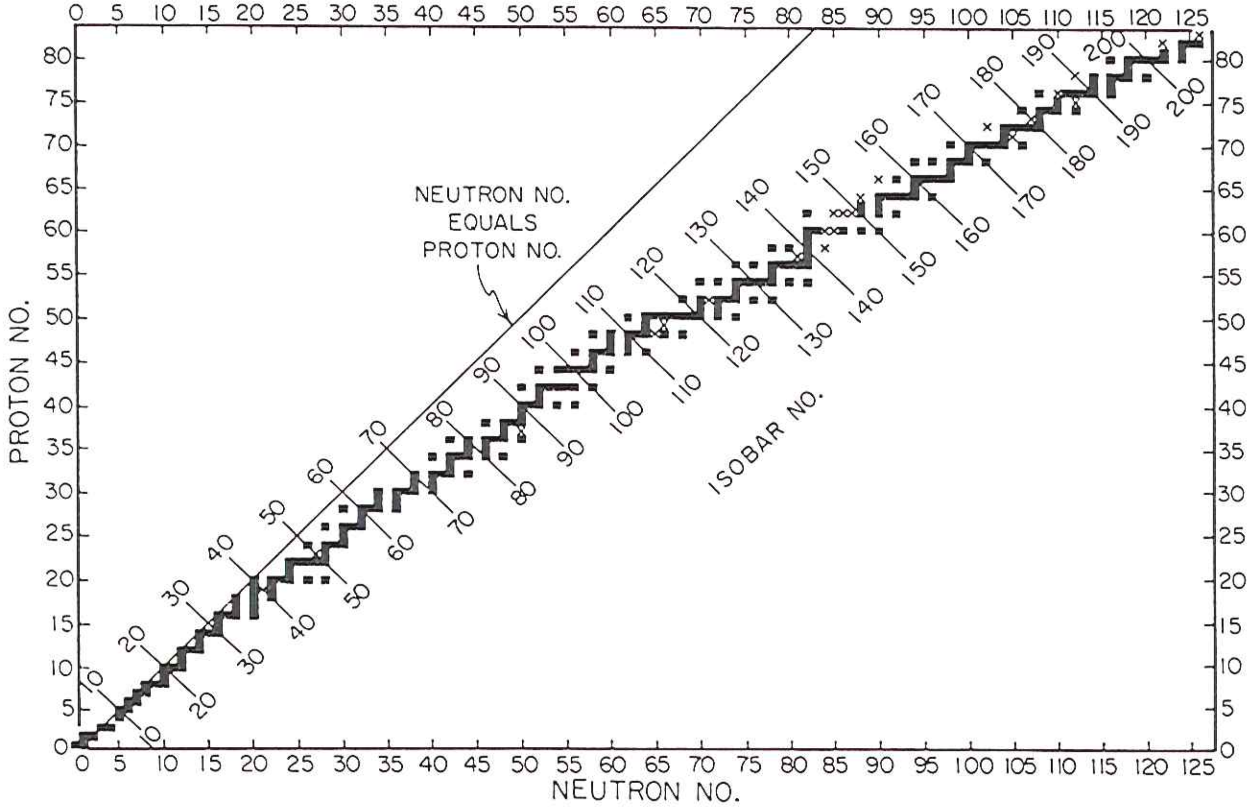
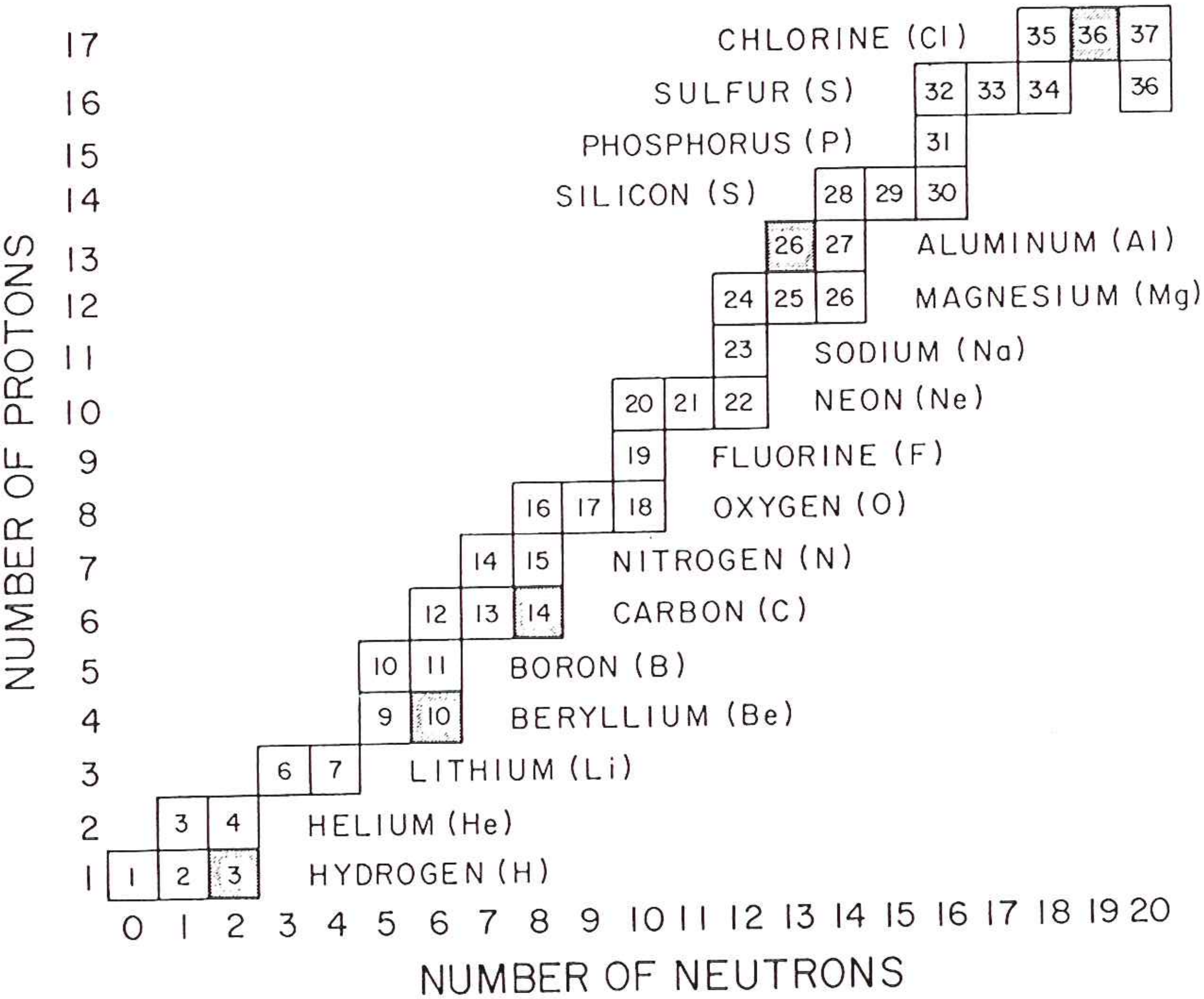
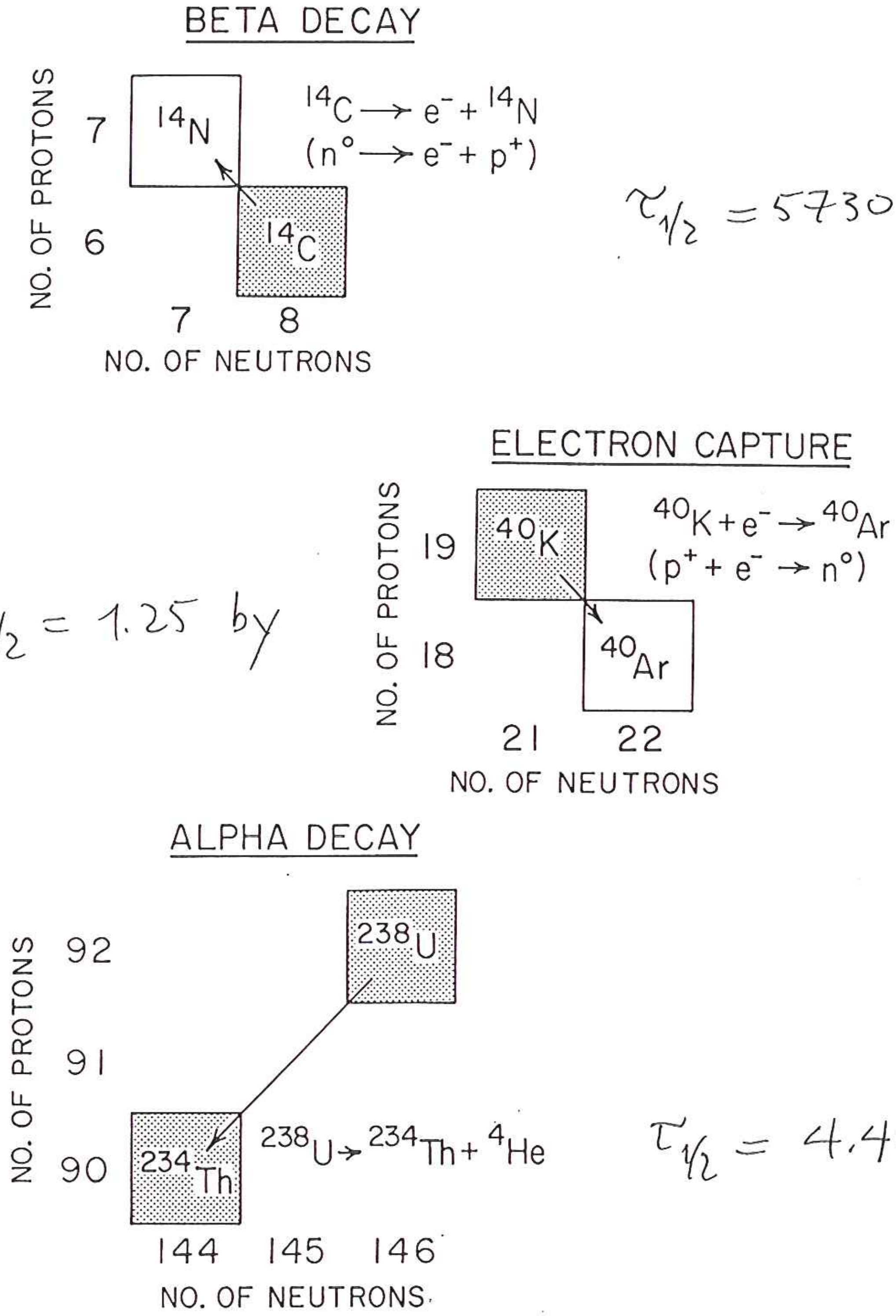


Figure 2-2. Stable nuclide configurations: The squares represent stable combinations of neutrons and protons. The x's represent radioactive nuclides whose half-lives are so long that they survive billions of years after their formation in stars. All the remaining combinations are radioactive with half-lives sufficiently short that they are no longer present in the solar system. Nuclides lying along the same horizontal line (i.e., those with the same proton number) are referred to as isotopes. Those falling along the same vertical line (i.e., those with the same number of neutrons) are referred to as isotones. Those falling along the same diagonal line (i.e., those with the same number of nuclear particles) are called isobars. The diagram terminates with the heaviest stable nuclide (^{209}Bi).

Figure 2-13. **Chart of the nuclides:** Shown in this series of diagrams are all the nuclides present in nature. The black squares represent radioactive isotopes. Some of these are long-lived remnants of element production in stars. Others are being produced in very small quantities by cosmic rays bombarding our atmosphere. To avoid confusion, the decay chains of long-lived thorium and uranium isotopes are shown separately.





$\tau_{1/2} = 5730$ yrs

$\tau_{1/2} = 1.25$ by

$\tau_{1/2} = 4.47$ by

Figure 2-3. Examples of the three most common modes of spontaneous radioactive decay: Two of these, beta decay and electron capture, are isobaric—i.e., the number of nucleons remains the same. The third, alpha decay, involves the ejection from the nucleus of four particles in the form of a ^{4}He nucleus.

Heavier elements $Z > 83$ unstable —
radioactive decay

Many lighter elements also have unstable isotopes above or below the stable Z versus N curve, e.g. ^{14}C (used for dating), ^{40}K (ditto)

Three types of decay

- β decay (neutron → proton)
- electron capture (proton → neutron)
- α decay — expel ^4He nucleus

See Fig 2-3 Broecker

Solar abundances

As noted we can determine chemical composition of Sun by inspection of Fraunhofer lines in solar spectrum

Fig 2-1 shows solar abundances

$$\boxed{Si = 10^6 \text{ atoms}}$$

Several noteworthy features:

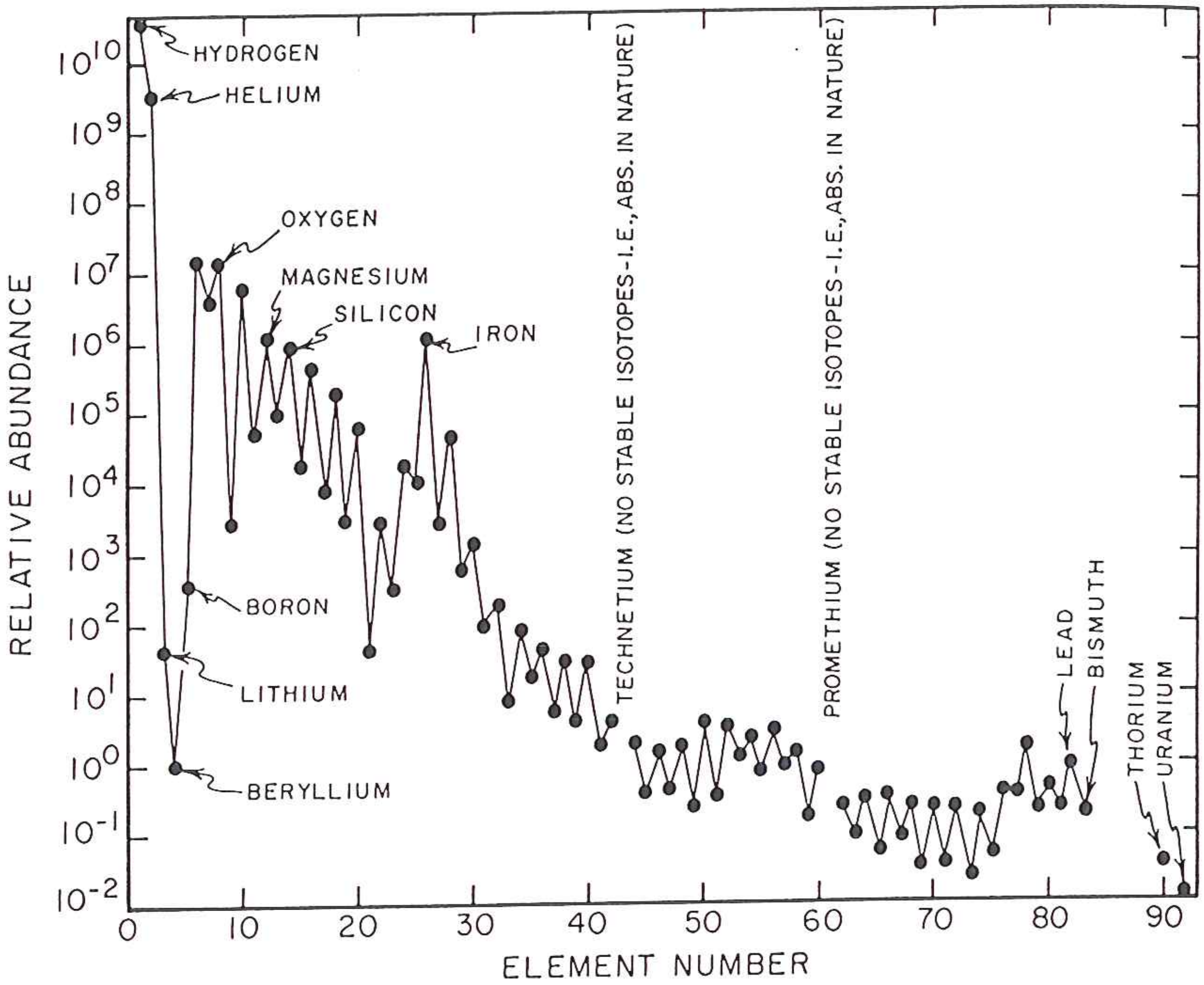


Figure 2-1. Relative abundances of the elements in our Sun: As the abundances range over 13 orders of magnitude, they must be displayed on a power-of-10 scale. The abundance of each element is expressed as the number of atoms per million (i.e., 10^6) atoms of the element silicon. The gaps in the sequence represent elements that have only radioactive isotopes and are, therefore, absent in the Sun. While most of the abundances are based on spectral data, use is made also of chemical measurements on a special class of meteorites called carbonaceous chondrites.

He/H = 1/16 ≈ 25% by weight

TABLE 1-7
Cosmic Abundances of the Elements (Atoms/10^6Si)

1	H	2.72×10^{10}	24	Cr	1.34×10^4	48	Cd	1.69	72	Hf	0.176
2	He	2.18×10^9	25	Mn	9510	49	In	0.184	73	Ta	0.0226
3	Li	59.7	26	Fe	9.00×10^5	50	Sn	3.82	74	W	0.137
4	Be	0.78	27	Co	2250	51	Sb	0.352	75	Re	0.0507
5	B	24	28	Ni	4.93×10^4	52	Te	4.91	76	Os	0.717
6	C	1.21×10^7	29	Cu	514	53	I	0.90	77	Ir	0.660
7	N	2.48×10^6	30	Zn	1260	54	Xe	4.35	78	Pt	1.37
8	O	2.01×10^7	31	Ga	37.8	55	Cs	0.372	79	Au	0.186
9	F	843	32	Ge	118	56	Ba	4.36	80	HG	0.52
10	Ne	3.76×10^6	33	As	6.79	57	La	0.448	81	Tl	0.184
11	Na	5.70×10^4	34	Se	62.1	58	Ce	1.16	82	Pb	3.15
12	Mg	1.075×10^6	35	Br	11.8	59	Pr	0.174	83	Bi	0.144
13	Al	8.49×10^4	36	Kr	45.3	60	Nd	0.836	90	Th	0.0335
14	Si	1.00×10^6	37	Rb	7.09	62	Sm	0.261	92	U	0.0090
15	P	1.04×10^4	38	Sr	23.8	63	Eu	0.0972			
16	S	5.15×10^5	39	Y	4.64	64	Gd	0.331			
17	Cl	5240	40	Zr	10.7	65	Tb	0.0589			
18	Ar	1.04×10^5	41	Nb	0.71	66	Dy	0.398			
19	K	3770	42	Mo	2.52	67	Ho	0.0875			
20	Ca	6.11×10^4	44	Ru	1.86	68	Er	0.253			
21	Sc	33.8	45	Rh	0.344	69	Tm	0.0386			
22	Ti	2400	46	Pd	1.39	70	Yb	0.243			
23	V	295	47	AG	0.529	71	Lu	0.0369			

Anders and Ebihara (1982).

Fe : Mg : Si : O ≈ 1 : 1 : 1 : 20

- Sun dominated by H and He

$H: 3 \cdot 10^{10}$ or $30{,}000 \times Si$
$He: 2 \cdot 10^{9}$ or $2{,}000 \times Si$

$\boxed{He/H = 1/16}$, i.e. 16 times as many H as He

But since atomic weight of He is 4

$\boxed{He/H \approx 25\% \text{ by weight}}$

- general decline with Z

- paucity of Be, Li, B

- peak near iron

- even – odd alternation (even more abundant, including Mg, Si, Fe, O)

use head of pin in room analogy to motivate question

[redacted]

The protons in the nucleus repel each other – but they are glued together by stronger nuclear force

Nuclear binding energy :

Can easily be measured by weighing atoms.

Example : ^4He – most abundant isotope of helium ~100%

^4He – 4.003 amu

Constituent parts

$2(1.0076)$
$+ 2(1.0090)$
$+ 2(0.0006)$

$2p + 2n + 2e^- = 4.034$ amu

Weighs less than sum of its parts.
Difference is nuclear binding energy

$$\boxed{E = mc^2 \quad \text{Einstein}}$$

c = speed of light = $3 \cdot 10^8$ m/sec

Binding energy of ^4He :

$$\overset{0.031 \text{ amu}}{(4.034 - 4.003 \text{ amu})} (1.67 \cdot 10^{-27} \text{ kg/amu}) (3 \cdot 10^8 \text{ m/sec})^2$$

$$E = 4.7 \cdot 10^{-12} \text{ Joules}$$

Generally measured in MeV = 10^6 electron volts

Table 2-1. Conversion of mass (m) to energy (E):

Einstein is famous for his equation: $E = mc^2$, where c is the velocity of light. If four hydrogen atoms are converted to one helium atom, the mass loss is as follows:

Mass of 4 hydrogen atoms	6.696×10^{-24} gm
Mass of 1 helium atom	-6.648×10^{-24} gm
Mass loss	0.048×10^{-24} gm

Using Einstein's equation, this mass loss generates about 1×10^{-12} calories of energy. If one gram of hydrogen is converted to helium, then about 1.5×10^{11} calories of energy are produced. With this amount of energy, about 2 million liters of water could be heated from room temperature to the boiling point.

$$\boxed{1 \text{ MeV} = 1.6 \cdot 10^{-13} \text{ J}}$$

$$\boxed{E = 29 \text{ MeV}}$$

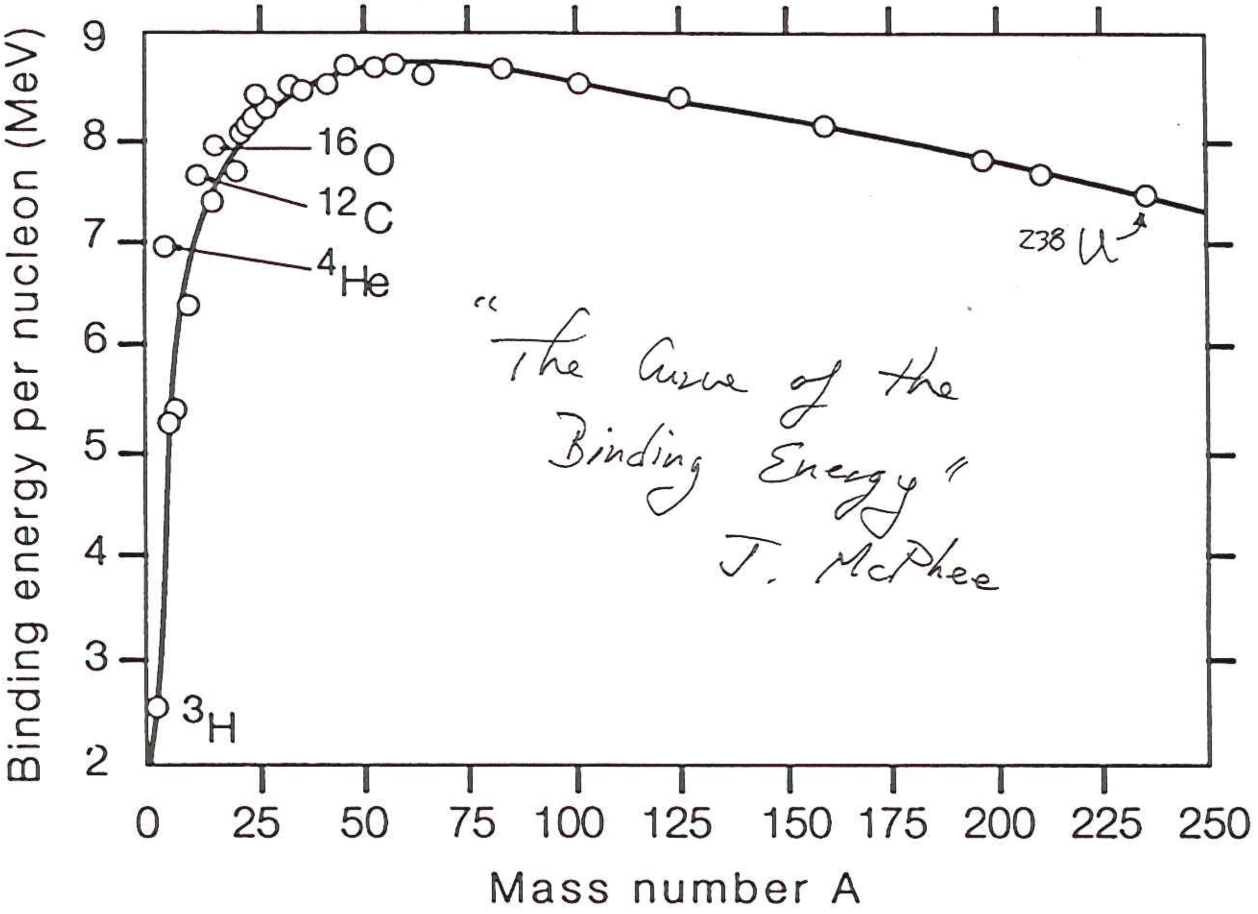
In general: $\boxed{1 \text{ amu} \times c^2 = 931 \text{ MeV}}$

$(0.031)(931) = 29$ MeV

$$\boxed{7 \text{ MeV / nucleon}}$$

Show Fig 4.37 — binding energy / nucleon versus mass number — Curve of the Binding Energy — peaks at ^{56}Fe

Below ^{56}Fe it is energetically favorable to bind neutrons and protons into nuclei, i.e. to fuse them — this can be done if they can be pushed together hard enough to overcome to Coulomb repulsion — requires very high temperatures — only present during big bang and in the interiors of stars — see Fig. 1.9 from Cox.



peck at 56Fe

26 protons
30 neutrons

238 U

"The Curve of the Binding Energy"
J. McPhee

Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

T of solar interior $\sim 2 \cdot 10^7$ K

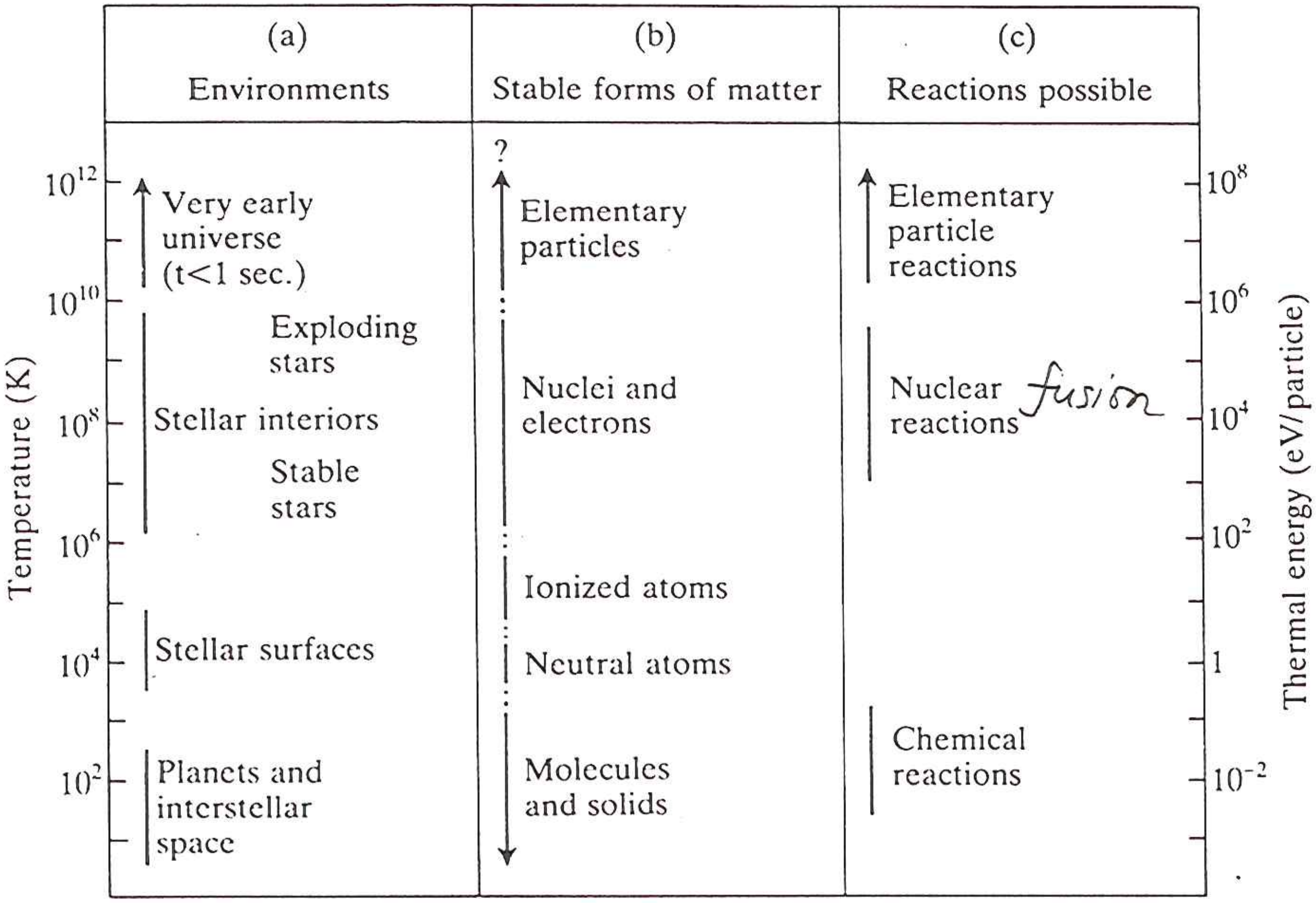


Fig. 1.9. Energy and temperature scales for chemical and nuclear processes. The scale on the left shows temperature, and that on the right indicates the average thermal energy for the particles present. Column (a) shows typical environments with different temperatures; (b) shows the stable forms of matter present; (c) indicates the types of reaction possible.

The H and He in the Sun & other stars were produced during the big bang ~ 15 b.y. ago

big bang [illegible] $T > 10^{10}$ K
^2H, ^3H, ^3He, ^4He all produced by collisions of $p = {}^1H$ and n during first three minutes

Although the very early stages are still uncertain, the picture becomes much clearer after the point where matter as we know it could form. After 1 second, the universe was composed of more familiar particles—protons, neutrons, electrons, neutrinos, and photons. Free neutrons would still be present in equilibrium at these temperatures, although they would soon start to undergo β^- decay into protons, electrons, and antineutrinos:

$$n = p^+ + e^- + \bar{\nu}. \tag{3.3}$$

As the temperature fell to around 10^9 K, more complex nuclei could start building up, by processes of fusion and neutron capture. The most important reactions, which were completed in a few minutes, were:

$$p + n = {}^2H + \gamma \tag{3.4}$$

$${}^2H + {}^2H = {}^3H + p \tag{3.5}$$

$${}^2H + {}^2H = {}^3He + n \tag{3.6}$$

$${}^3He + n = {}^4He + \gamma \tag{3.7}$$

$${}^3H + p = {}^4He + \gamma \tag{3.8}$$

Under the conditions present, it was certainly the first of these reactions—the formation of deuterons (^2H)—that constituted the rate-limiting step. This is because of the rather low binding energy of deuterons (2.2 MeV), so that they would be dissociated almost as rapidly as they formed. The remaining reactions occurred rapidly, and ^4He was by far the major product. The proportions of deuterium and ^3He remaining from this early stage of nucleosynthesis are very sensitive functions of the density of matter and so are a useful indicator of the conditions present at that time. On the other hand, the amount of helium produced depends less strongly on the density, and is largely determined by the equilibrium ratio of neutrons to protons at the temperature when the nuclear reactions can begin. Calculations predict a He/H atomic ratio of nearly ~~1:10~~, or about 25 per cent helium by weight. This is the abundance observed in stars, and is one of the strongest pieces of evidence that the big bang theory is correct.

1:16

Element formation during the first three minutes

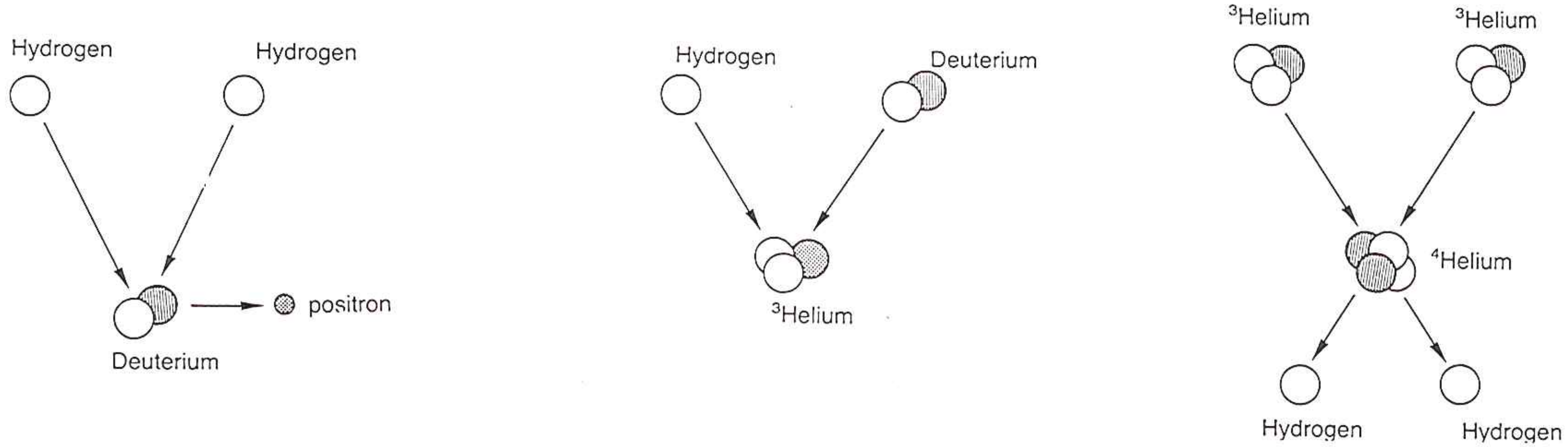


Figure 2.2

Hydrogen burning, the proton-proton chain, is an important energy-producing nuclear reaction that takes places inside stars like our Sun. In this process two hydrogen (H) nuclei combine to form a deuterium (D, hydrogen with an atomic weight of 2) nucleus and a positron (electron with a positive charge). Neutrons are shaded; protons are white. Reaction with an additional hydrogen nucleus produces a helium nucleus with a mass of three (^{3}He). The fusion of two such nuclei results in the production of stable helium (^{4}He, which has two protons) and the ejection of two hydrogen nuclei, which can be consumed in other reactions of this sort. Energy is released by these reactions as a small amount of matter is converted into energy in accordance with Einstein's equation, E (energy) = m (mass converted to energy) c^2 (the speed of light squared).

← also during BIG BANG

No elements beyond ^4He produced – why

One reason – no stable elements with
$A = Z + N = 5$ or 8

Thus ^5He and ^5Li both unstable –
~~[illegible]~~ half lives of both
about 10^{-21} secs.

^7Li (most abundant 92%) can be
produced by $^4He + {}^3H \rightarrow {}^7Li$

~~But by the time T had dropped and density ρ dropped~~

But by the time there was enough
^4He and ^3He to produce much ^7Li
the temp T and density ρ had
dropped enough to mean no more
reactions

Thus, three minutes after $t = 0$ the
Universe consisted of H and He in
ration $He/H = 25\%$ by weight and
nothing else.

$\overline{T}_{\text{Big Bang}} \approx 10^{11} - 10^{12}$ K

The universality of $He/H = 25\%$ in all stars
is one of strongest pieces of evidence for big bang

Although the very early stages are still uncertain, the picture becomes much clearer after the point where matter as we know it could form. After 1 second, the universe was composed of more familiar particles—protons, neutrons, electrons, neutrinos, and photons. Free neutrons would still be present in equilibrium at these temperatures, although they would soon start to undergo β^- decay into protons, electrons, and antineutrinos:

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Under the conditions present, it was certainly the first of these reactions—the formation of deuterons (^2H)—that constituted the rate-limiting step. This is because of the rather low binding energy of deuterons (2.2 MeV), so that they would be dissociated almost as rapidly as they formed. The remaining reactions occurred rapidly, and ^4He was by far the major product. The proportions of deuterium and ^3He remaining from this early stage of nucleosynthesis are very sensitive functions of the density of matter and so are a useful indicator of the conditions present at that time. On the other hand, the amount of helium produced depends less strongly on the density, and is largely determined by the equilibrium ratio of neutrons to protons at the temperature when the nuclear reactions can begin. Calculations predict a He/H atomic ratio of nearly ~~1:10~~, or about 25 per cent helium by weight. This is the abundance observed in stars, and is one of the strongest pieces of evidence that the big bang theory is correct.

1/16

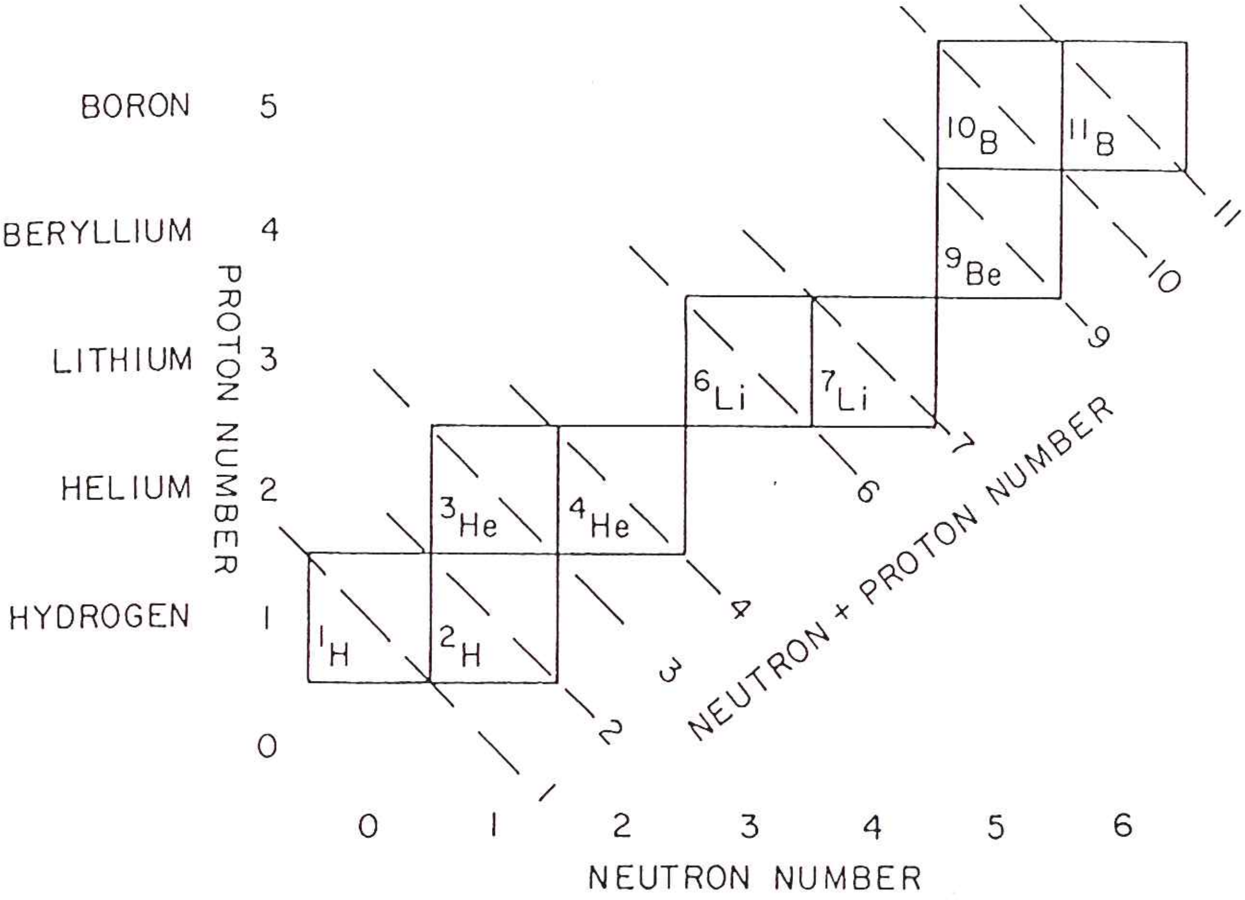


Figure 2-4. Stable nuclides with a particle number in the 1-to-11 range: Note that no stable nuclide exists with neutron-plus-proton number totaling 5 or 8. It is these two gaps in the chain that prevented element formation during the big bang from continuing beyond helium.

All other elements produced subsequent to big bang by nuclear burning in stars.

$$\boxed{T_{\text{stellar interiors}} \approx 10^7 - 10^9 \text{ K}}$$

Sun-sized stars $(M = M_\odot)$ can burn only H to make He — they become red giants after they have consumed about 1/4 of their H.

But in bigger stars, T is higher, enough to overcome the Coulomb repulsion and produce heavier elements, e.g.

$${}^4He + {}^4He \rightarrow {}^8Li$$

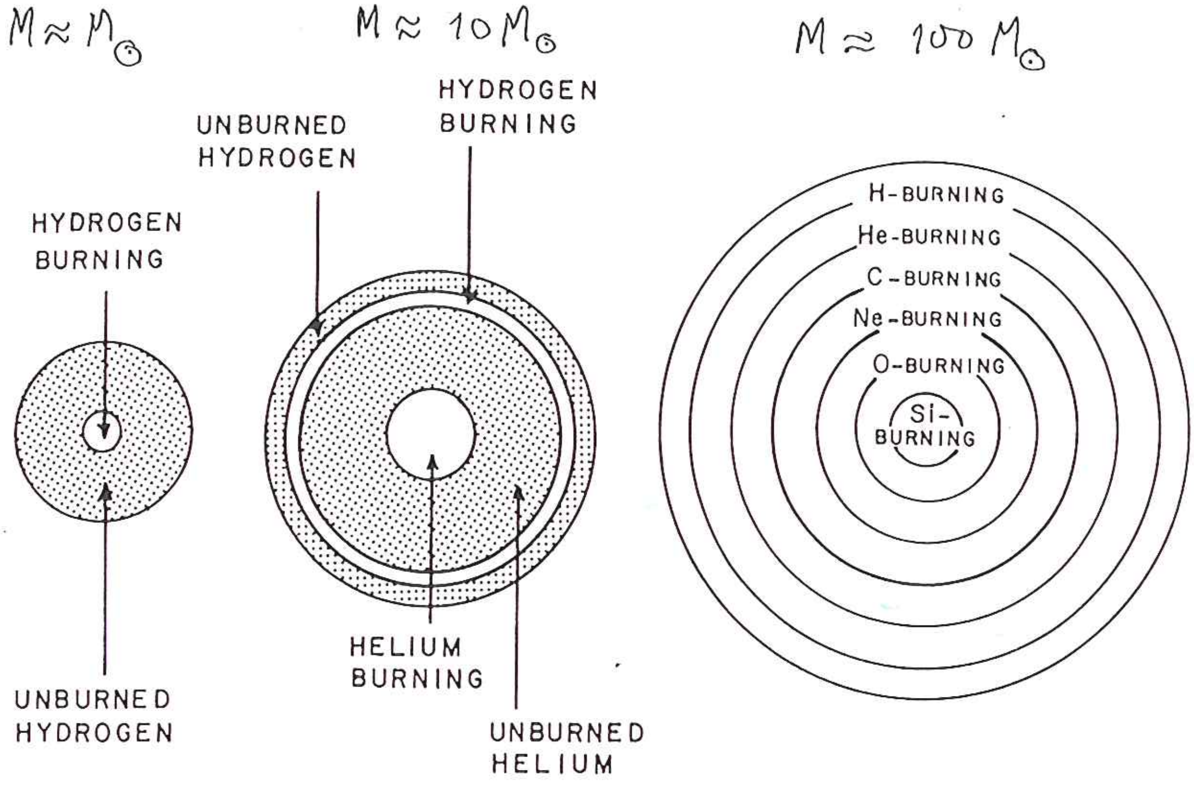
also $^4He + {}^3H \rightarrow {}^7Li$

Carbon is made by   2 most abundant

$${}^4He + {}^8Be \rightarrow {}^{12}C$$

And oxygen by $^4He + {}^{12}C \rightarrow {}^{16}O$

Fig 2-5 Broecker compares the onion-skin structure of stars with $M = M_\odot$, $10 M_\odot$, $100 M_\odot$



Name of Process	Fuel	Products	Temperature
Hydrogen-Burning	H	He	60 × 10^6 °K
Helium-Burning	He	C, O	200 × 10^6 °K
Carbon-Burning	C	O, Ne, Na, Mg	800 × 10^6 °K
Neon-Burning	Ne	O, Mg	1500 × 10^6 °K
Oxygen-Burning	O	Mg to S	2000 × 10^6 °K
Silicon-Burning	Mg to S	Elements near FE	3000 × 10^6 °K

Figure 2-5. Three stars with progressively hotter nuclear fires: Like our Sun, the star at the left burns hydrogen to form helium in its core; this core is surrounded by unburned fuel. The middle star is burning helium to form carbon and oxygen in its core. This core is surrounded by a layer of unburned helium. Outside of this is a layer in which hydrogen burns to produce helium. Finally there is an outer layer of unburned hydrogen. The star on the right has a multilayered fire. The successive nuclear fires are separated by layers in which no reaction occurs. These layers contain the same fuel as is being consumed in the underlying fire. These layers are depleted in the ingredient being consumed in the overlying fire. The approximate temperatures required to ignite the successive fuels are also given.

$T_{\text{stellar interiors}} \approx 10^7 - 10^9$ K

Elements up through [redacted] Fe can be made in this way — by nuclear burning

Above Fe the binding energy / nucleon decreases — no longer energetically favorable to fuse protons and neutrons

Elements above Fe produced by another process — which can occur at room temperature — neutron capture

No Coulomb barrier to neutron capture.

Neutrons are produced by many reactions during burning, e.g.

$$^{13}C + {}^{4}He \rightarrow {}^{16}O + n$$

$$^{12}C + {}^{12}C \rightarrow {}^{23}Mg + n$$

Fig 2-8 shows how neutron capture and β decay of unstable nuclides can produce elements above Fe

Note that there are some stable elements [redacted] which cannot be produced by this so-called slow or s process.

no longer energetically favorable to fuse nuclei above ^{56}Fe.

peak at ^{56}Fe

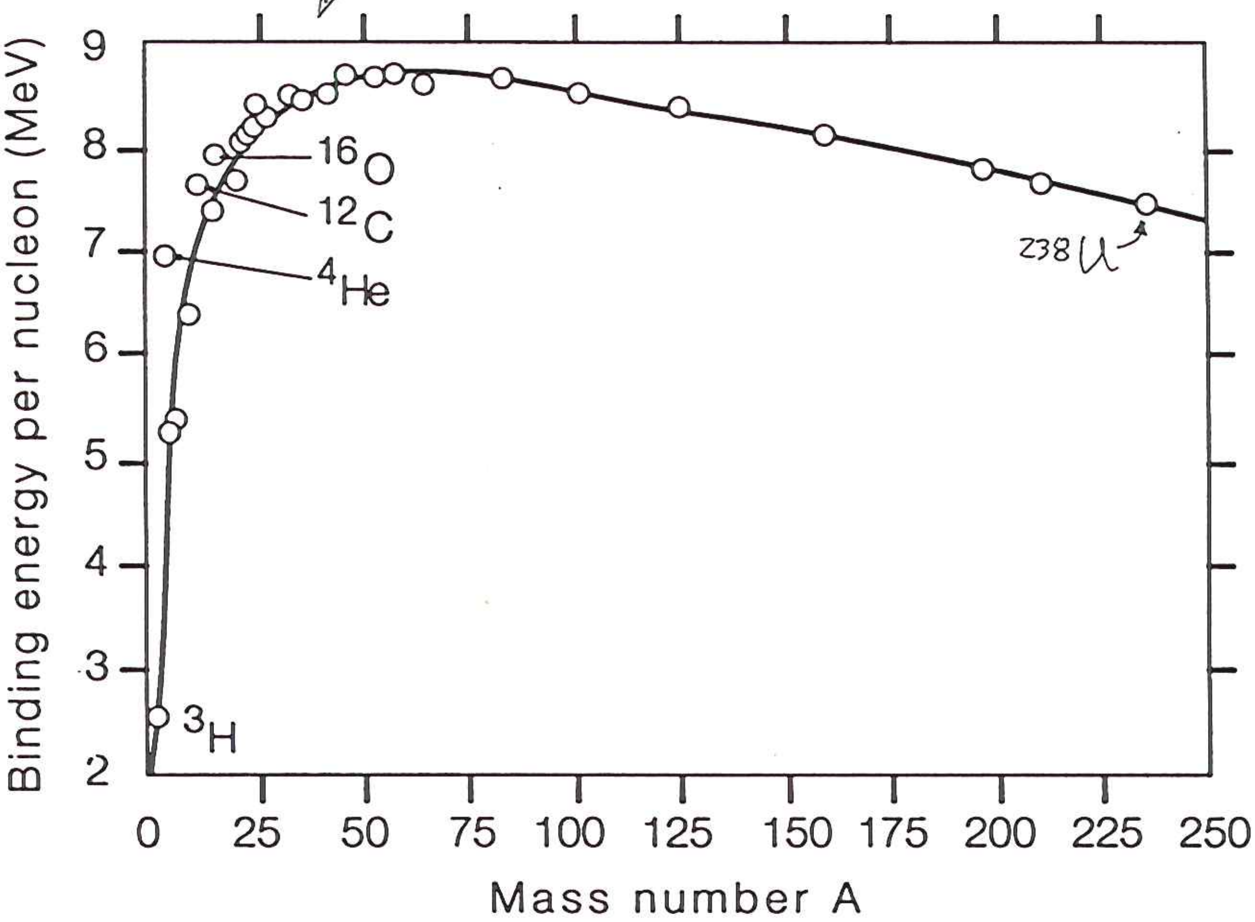
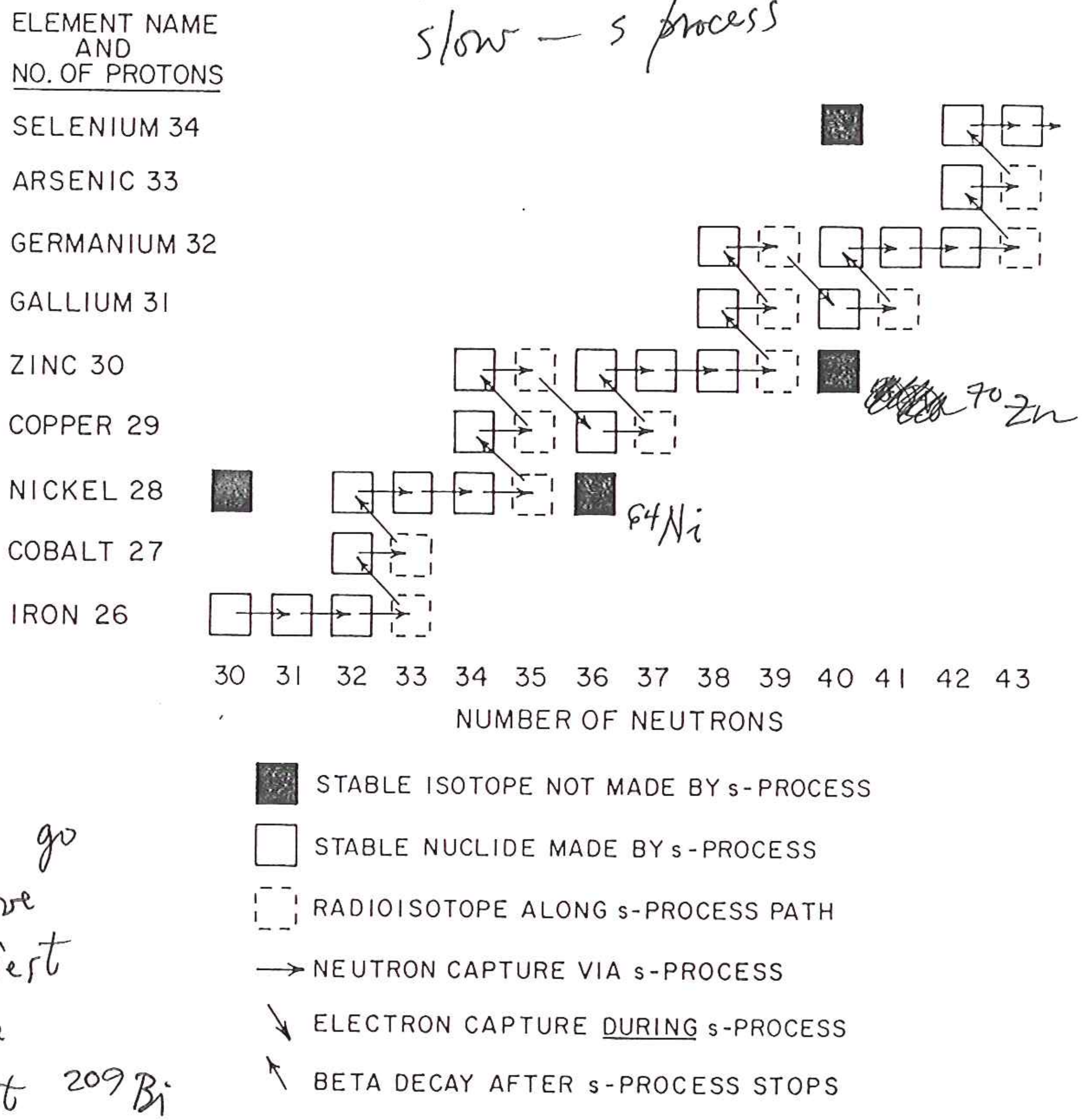


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

Element formation in stars above ^{56}Fe
by neutron capture
slow – s process



can't go
above
heaviest
stable
element ^{209}Bi

Figure 2-8. Details of the s-process path: Each time neutron capture produces a radioactive isotope, radiodecay occurs changing either a neutron into a proton or a proton into a neutron. Not all of the stable isotopes found in solar-system matter can be produced in this way. Those stable isotopes lying below the s-path are produced by the r-process. Those stable isotopes lying above the s-path are produced by proton bombardment.

For example, ^{64}Ni cannot be made because it is blocked by the decay of ^{63}Ni

Also, s processes cannot synthesize elements heavier than ^{209}Bi, the heaviest stable element

Why — because neutron captures are infrequent — plenty of time for β decay to occur — i.e., basically the same reason ^{63}Ni can't be made.

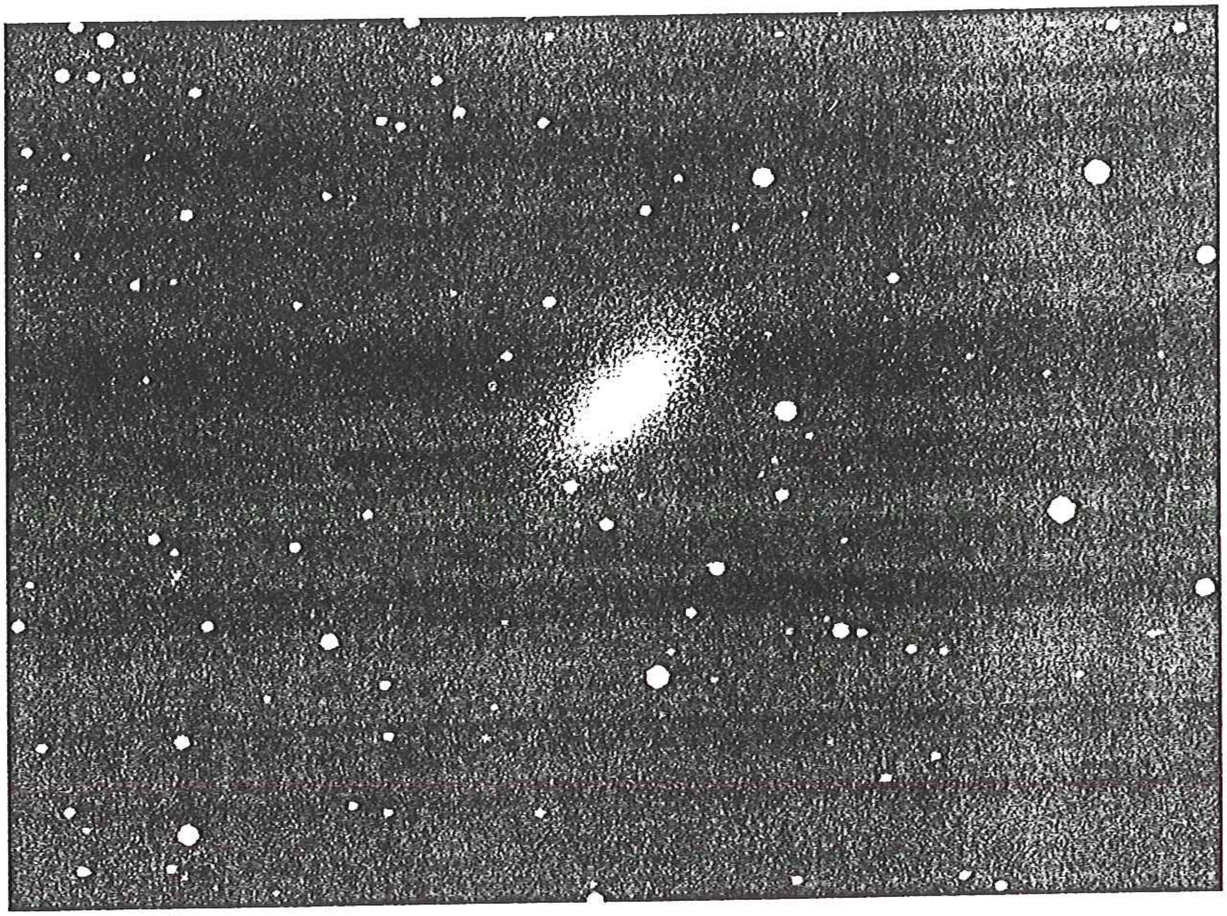
Most of the remaining elements are made during supernova explosions — stars heavier than 2.2 $M_\odot$ collapse to form neutron stars when they exhaust their fuel — temp $T \rightarrow 10^{10}$ K.

So many neutrons are captured that there is no time for β decay to occur.

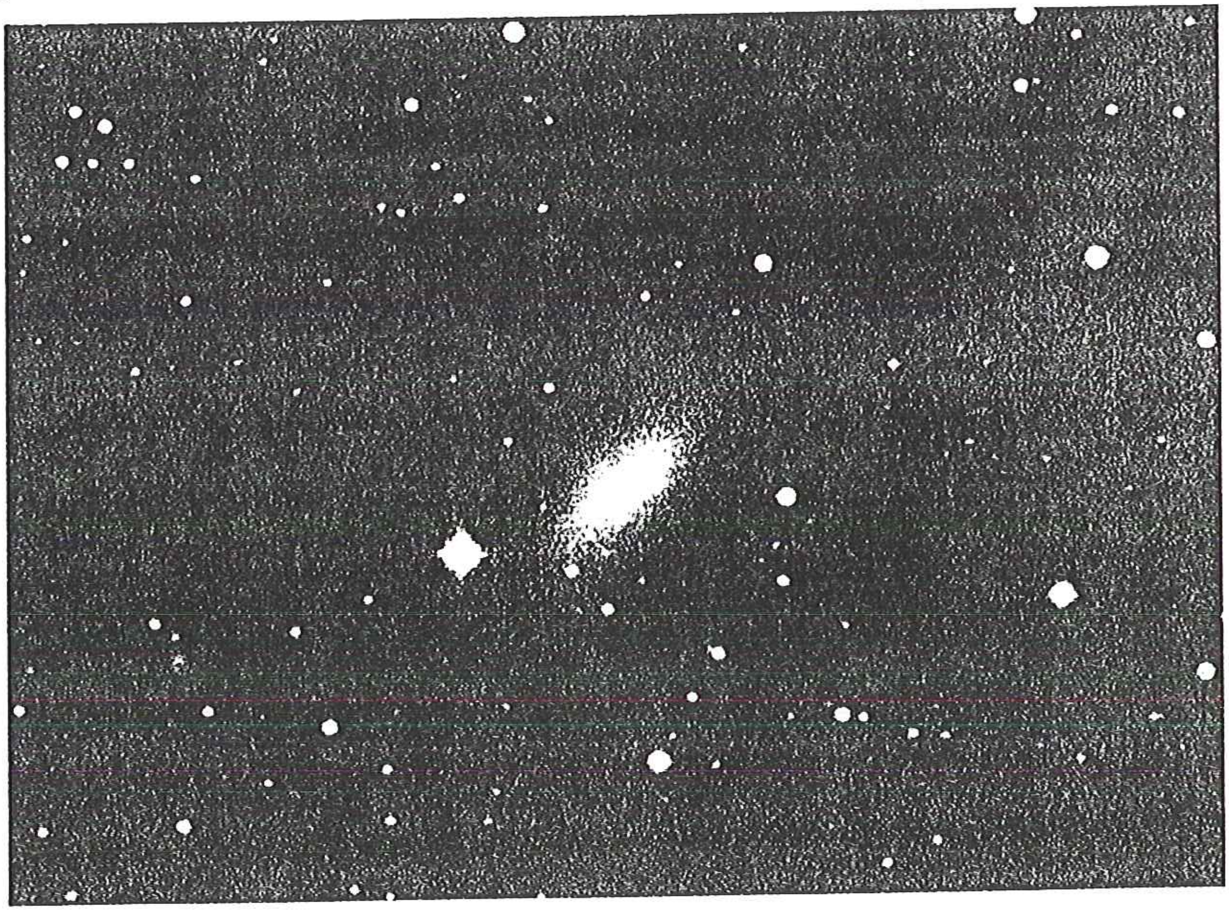
This produces very unstable neutron-rich nuclei along the r-process (r = rapid) path in Fig 2-6.

These then proceed to decay to form the stable r-process isotopes.

Figure 2-9. Evidence for supernova explosions: Photographs taken before and after a supernova explosion.



June 1959



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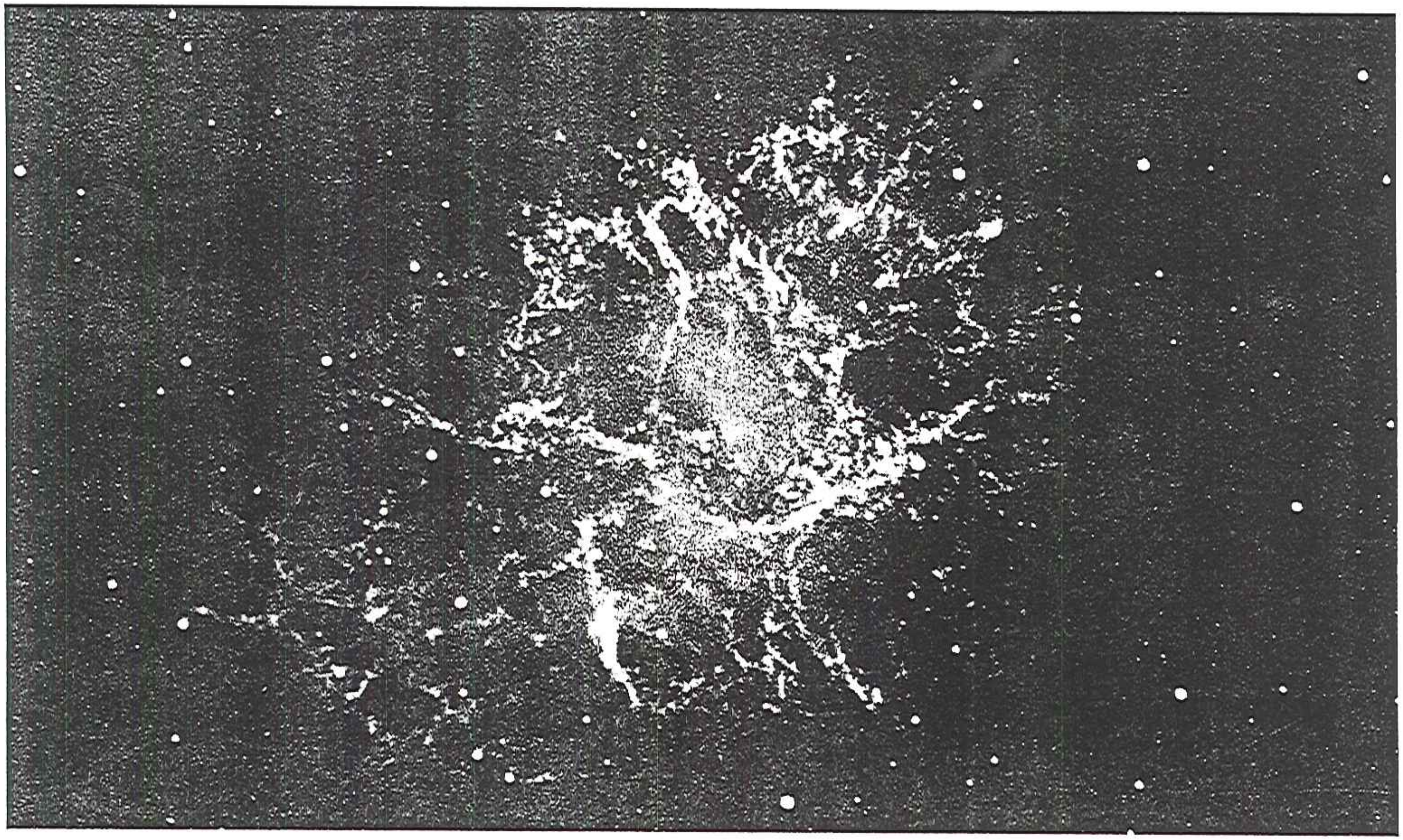


Figure 2.4

The Crab nebula is the remnant of a supernova explosion of a massive star. This chaotic mass of expanding gas and dust is correlated with the description of a supernova seen by Chinese astronomers in A.D. 1054. Such explosions are an important method of injecting newly formed elements into interstellar space, where they may eventually be recycled to form other generations of stars and planets.

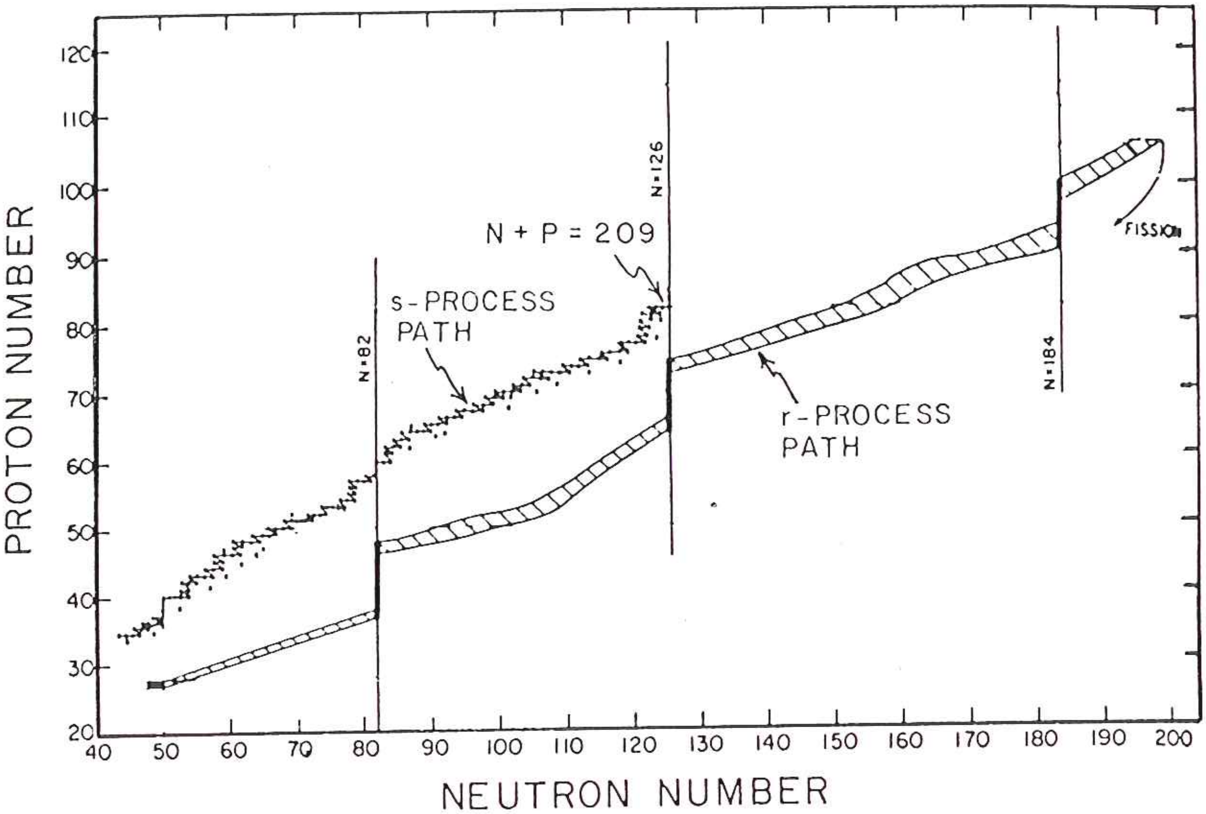


Figure 2-6. The elements heavier than iron were built by neutron irradiation: Two quite different processes contributed to this production. One, the s-process (i.e., slow process), occurs concurrently with the production of iron in the stellar core. As in a nuclear reactor, the reaction proceeds in a controlled way. Neutron hits are spaced out in such a way that the nuclides have time to achieve stability through beta decay. Thus, the buildup path follows the belt of stability shown in Figure 2-2. For the same reason it terminates at ^{209}Bi, the heaviest stable nuclide.

The r-process (i.e., the rapid process) occurs during the supernova explosion. Thus, it is akin to an atomic bomb. No sooner has a nuclide absorbed one neutron than it is hit by another. No time exists between hits for radiodecay. Rather, radiodecay occurs only when the nuclide becomes so neutron-rich that it cannot absorb any more. This leads to a buildup path displaced from the stability belt as shown. It also allows the buildup to proceed beyond particle number 209. Instead, the buildup goes just beyond particle number 300. At this point the colliding neutrons cause the nuclides to fission. The jogs in the r-process pathway occur at the so-called magic neutron numbers, 82, 126, and 184. They are "magic" in the sense they give the nuclide unusual stability.

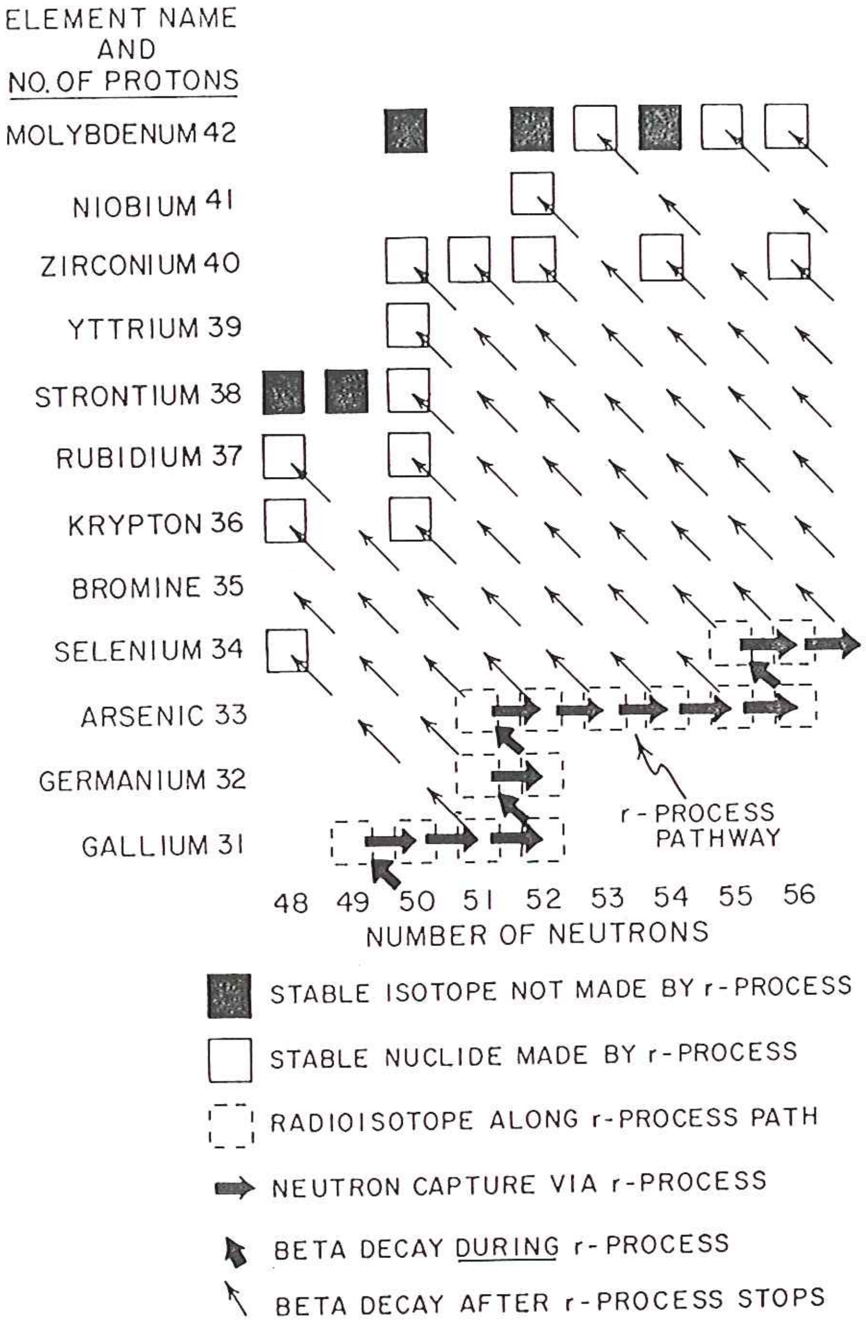
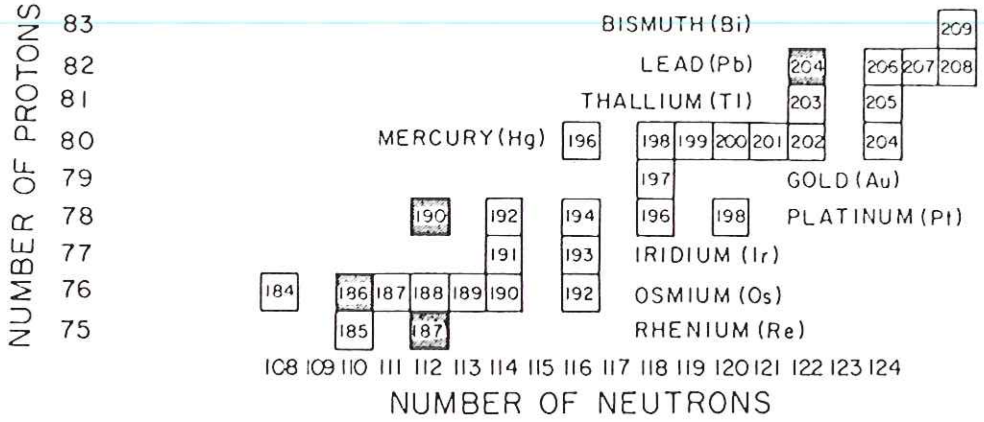
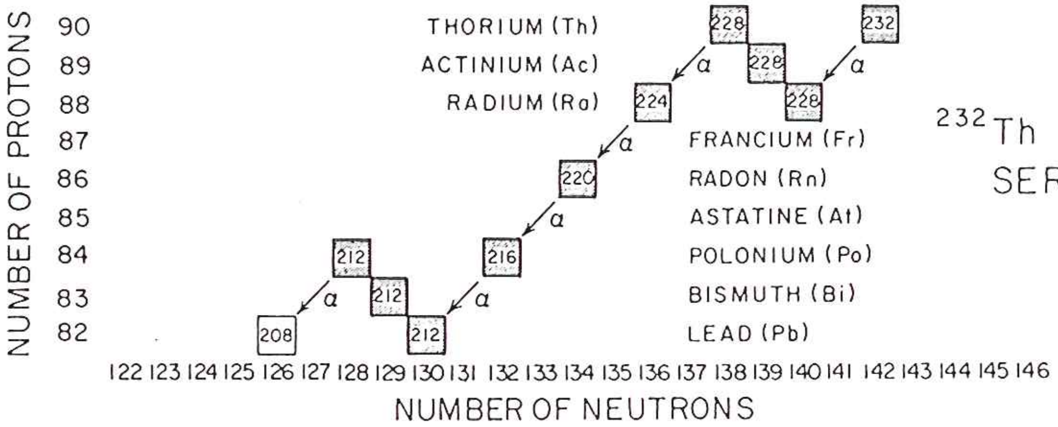


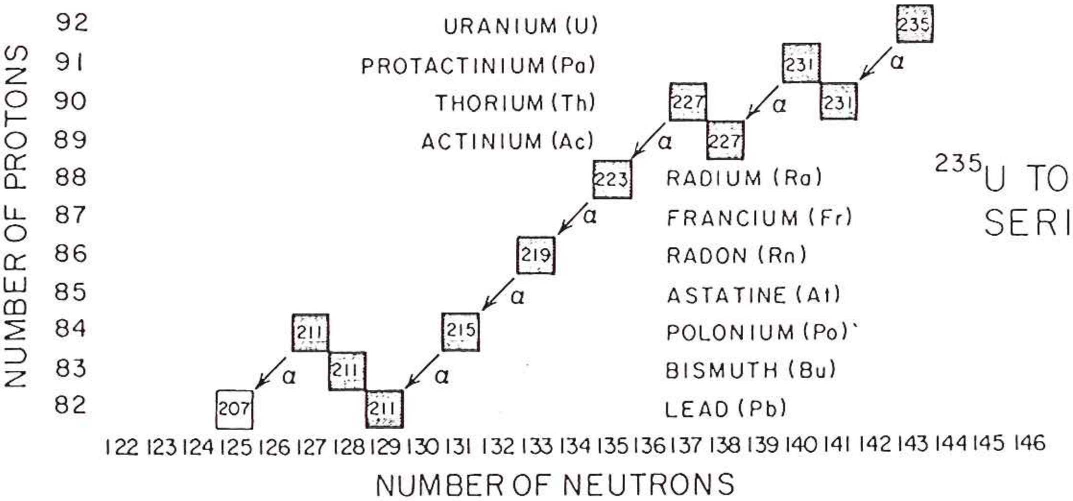
Figure 2-7. A segment of the r-process pathway: Rapid-fire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.



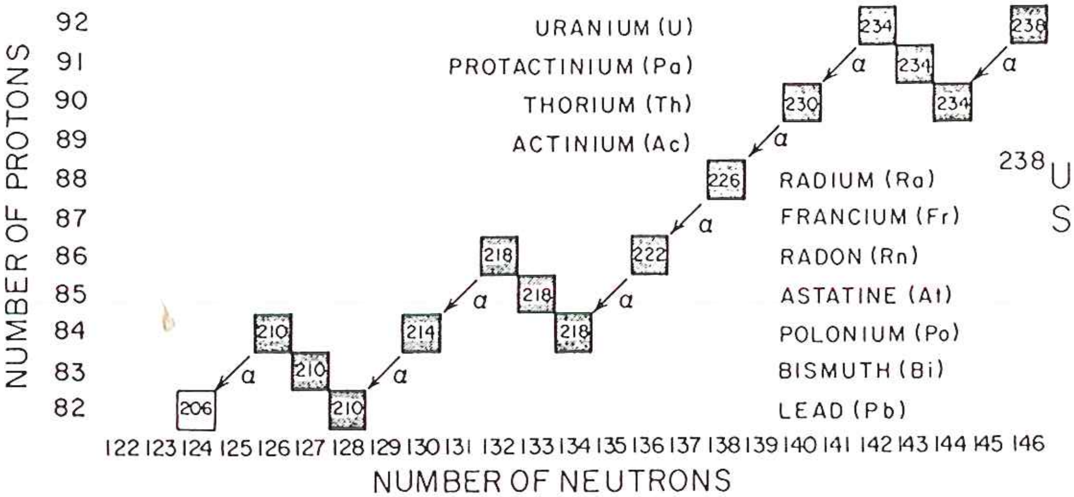
← all elements above here produced by r process in supernovae



^{232}Th TO ^{208}Pb SERIES



^{235}U TO ^{207}Pb SERIES



^{238}U TO ^{206}Pb SERIES

The three U-Pb and Th-Pb radioactive decay chains are also produced by the r-process.

The net result is that the supernova explodes and releases both its r-process and s-process elements into space

There they can be accumulated into a new star such as the Sun and its surrounding planets

By measuring neutron capture cross sections, β-decay times, nuclear burning cross sections, and by modelling the T and P in an evolving and then exploding star, we can predict the abundance of the various isotopes released by a given supernova

See, e.g., Fig. 3.5 from Cox for a single $M = 25 M_\odot$ supernova — includes all 3 types of nuclei

- burning produced
- s process neutron capture
- r process neutron capture

The quantity plotted is

$$\frac{(\#\text{ atoms} / \#\, H \text{ atoms})_{\text{released by explosion}}}{(\#\text{ atoms} / \#\, H\text{ atoms})_{\text{solar abundance}}}$$

It is seen that for most elements this ratio is ~ 10

Thus ~ 1/10 of the ~~[illegible]~~ H and He in the sun has been processed through other stars and then released by supernova explosions.

The remaining ~9/10 is unprocessed H and He from the big bang.

All aspects of the solar abundance curve can be understood on the basis of the nuclear physics of burning and neutron capture. Let's discuss a few examples:

- paucity of Li, Be, Bo — very little if any produced in * for same reason none produced in big ~~[illegible]~~ bang — absence of stable $A = 5$ and $A = 8$ isobars

Figure 3.5 shows the results of a recent calculation on the elements liberated in a supernova. The relative amount of each nuclide produced from a star of 25 solar masses has been compared with the observed solar system abundances. Many common elements such as iron and

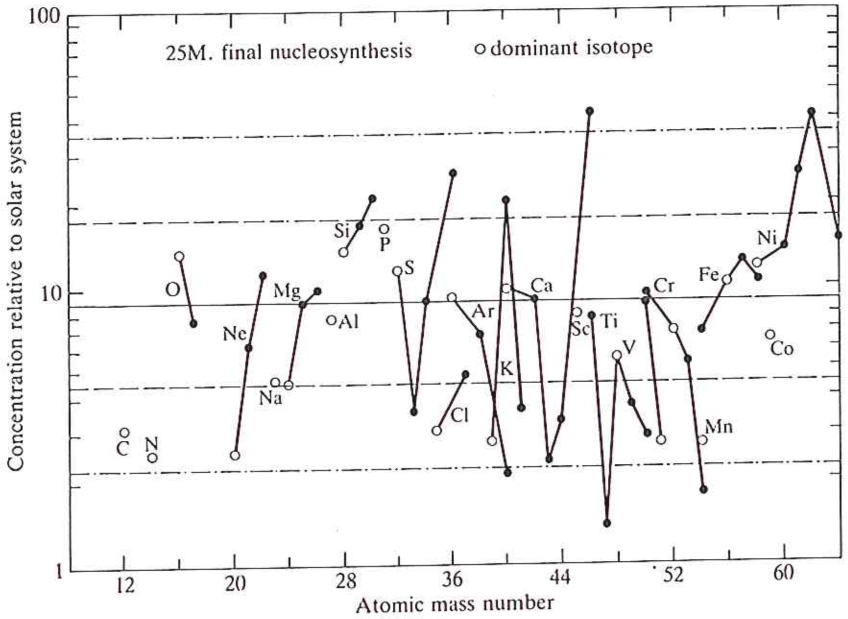


Fig. 3.5. Calculation of the elements produced by a supernova in a star of 25 solar masses. (From Woosley and Weaver 1986.) The predicted concentration of each nuclide has been compared with its observed solar system abundance. The calculation suggests that about one part in nine of the material forming the solar system has been produced by such supernovae.

oxygen are predicted to have a concentration nine times that found in the solar system. This means that their observed abundances can be accounted for if one part in nine of the material in the solar system was generated in a supernova, the remaining eight-ninths being unprocessed hydrogen and helium. There is a fair amount of scatter in the figure, but the overall agreement is impressive, especially when it is remembered that the *absolute* abundances of the nuclides plotted span a factor of more than 10^7. In fact, there is no reason to think that a calculation on a single star could explain perfectly the abundances of elements in the solar system. Stars of different masses burn at different rates, and the various reaction stages occur to different extents. For example, stars rather lighter than the one calculated will probably produce more carbon and less oxygen. The composition of the gas released will reflect these differences, and one ought to take some kind of average over the yields of stars with a range of mass. It is also important to note that supernovae are not the *only* way in which elements are released into space. Stars at some stages in their evolution may throw off part of their outer layers, either gradually over millions of years, or in a more rapid process. These outer layers will be enriched in rather different elements, for example, in nitrogen and ^{13}C produced in the CNO cycle. There is every reason to think that the gas from which the solar system formed was made up of a mixture from many different sources. No single event, therefore, can account for the abundances of the elements. In spite of these problems, the calculation illustrated in Fig. 3.5 is very encouraging and does suggest that present theories explain these abundances quite well.

Cox
The
Elements

$$\frac{\left(\#\text{atoms}/\#H\right)_{\text{explosion}}}{\left(\#\text{atoms}/\#H\right)_{\text{solar abundance}}}$$

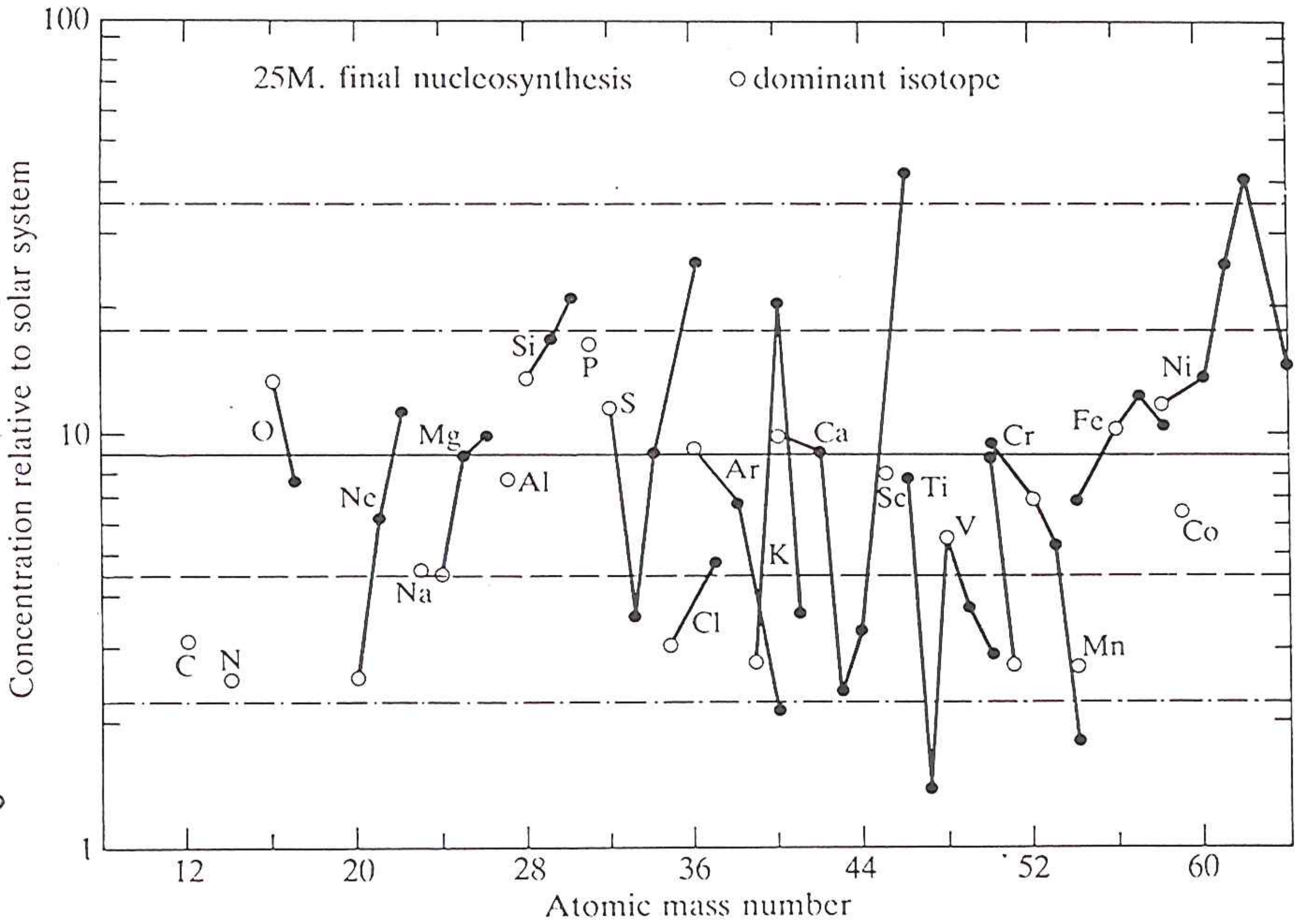


Fig. 3.5. Calculation of the elements produced by a supernova in a star of 25 solar masses. (From Woosley and Weaver 1986.) The predicted concentration of each nuclide has been compared with its observed solar system abundance. The calculation suggests that about one part in nine of the material forming the solar system has been produced by such supernovae.

Here is the argument, presumably:

$$\frac{Fe_{SN}}{H_{SN}} \frac{H_{\odot}}{Fe_{\odot}} \simeq 10$$

But $Fe_{\odot} = Fe_{SN}$ (all the Fe in the Sun is from supernovae)

Thus $H_{\odot} \simeq 10 H_{SN}$

- peak at ^{56}Fe (Fig. 2-10) most stable element — lots produced in core of massive stars — then they explode and release it

- even-odd alternation
  elements with an <u>even</u> number of neutrons + protons are more abundant

reason for this shown in Fig. 2-14 mass trends along $A = 102$ and $A = 103$ isobars

only one stable $A = 103$ (^{103}Rh) but two stable $A = 102$ isotopes (^{102}Ru and ^{102}Pa) — see Broecker chart of nuclides.

ditto two $A = 104$, one $A = 105$, two $A = 106$, one $A = 107$ etc.

<u>Sometimes</u> there can be more than one A=odd, e.g. $A = 87$ or more than two A=even, e.g. $A = 96$.

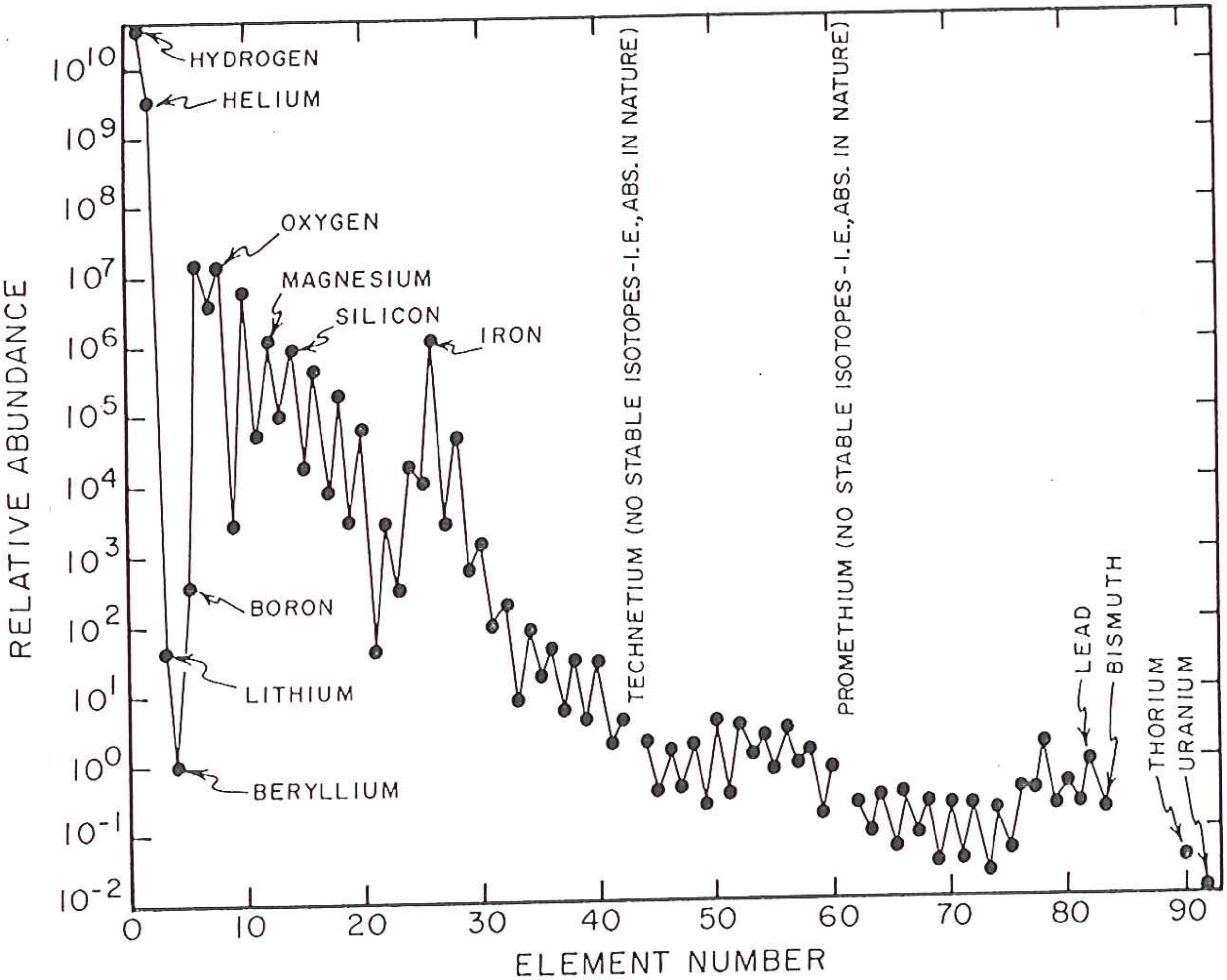


Figure 2-1. Relative abundances of the elements in our Sun: As the abundances range over 13 orders of magnitude, they must be displayed on a power-of-10 scale. The abundance of each element is expressed as the number of atoms per million (i.e., 10^6) atoms of the element silicon. The gaps in the sequence represent elements that have only radioactive isotopes and are, therefore, absent in the Sun. While most of the abundances are based on spectral data, use is made also of chemical measurements on a special class of meteorites called carbonaceous chondrites.

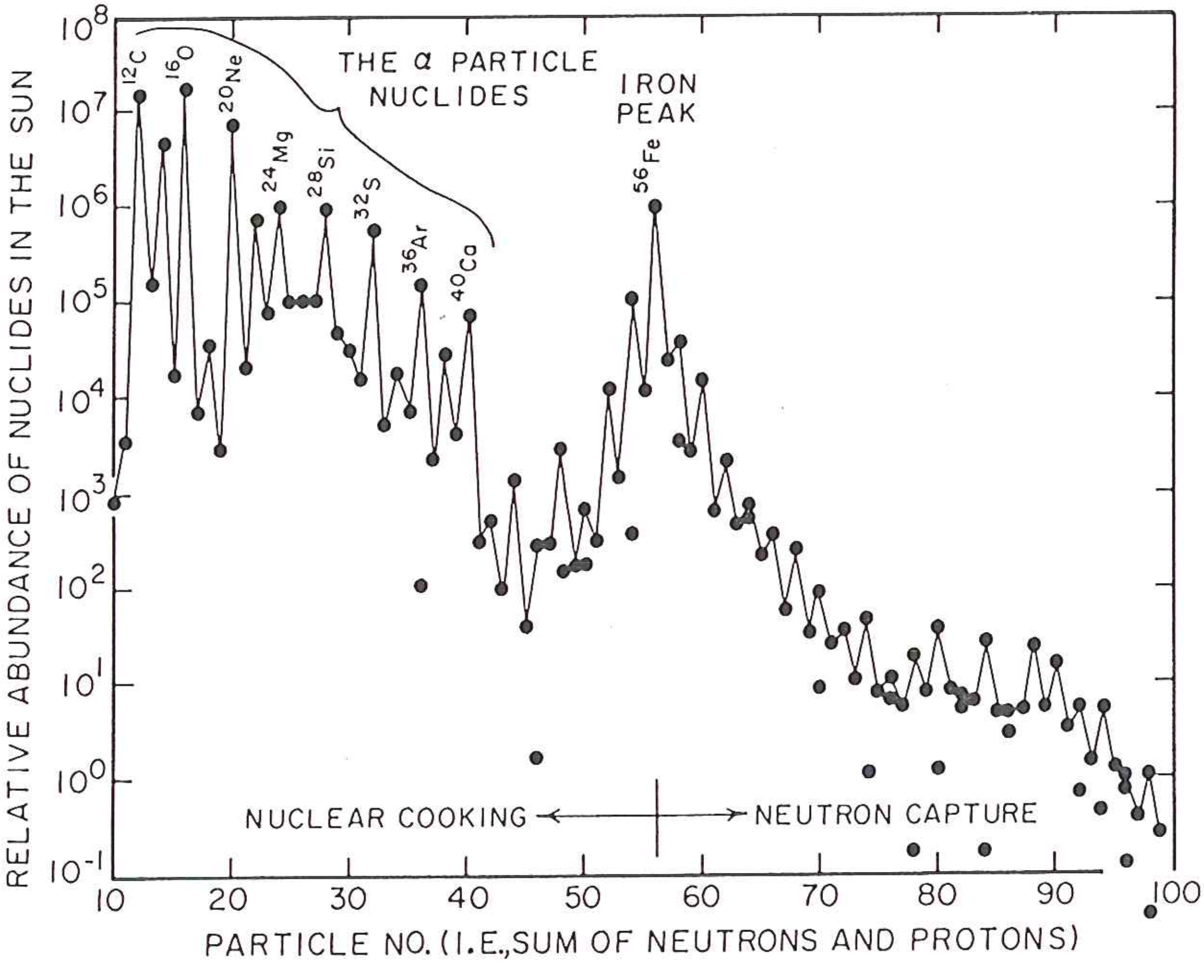


Figure 2-10. Relative abundances of individual nuclides: In the mass range 10 to 50, nuclides with particle numbers divisible by 4 (i.e., 12, 16, 20, 24, 28, 32 . . .) have abundances far above those of their neighbors. They are referred to as the *α*-particle nuclides. In the particle number range 50 to 100 the abundances of nuclides with an even particle number stand about a factor of 3 above those for their odd-numbered neighbors. Where more than one point is shown at a given mass number, two different nuclides with the same neutron-plus-proton number exist.

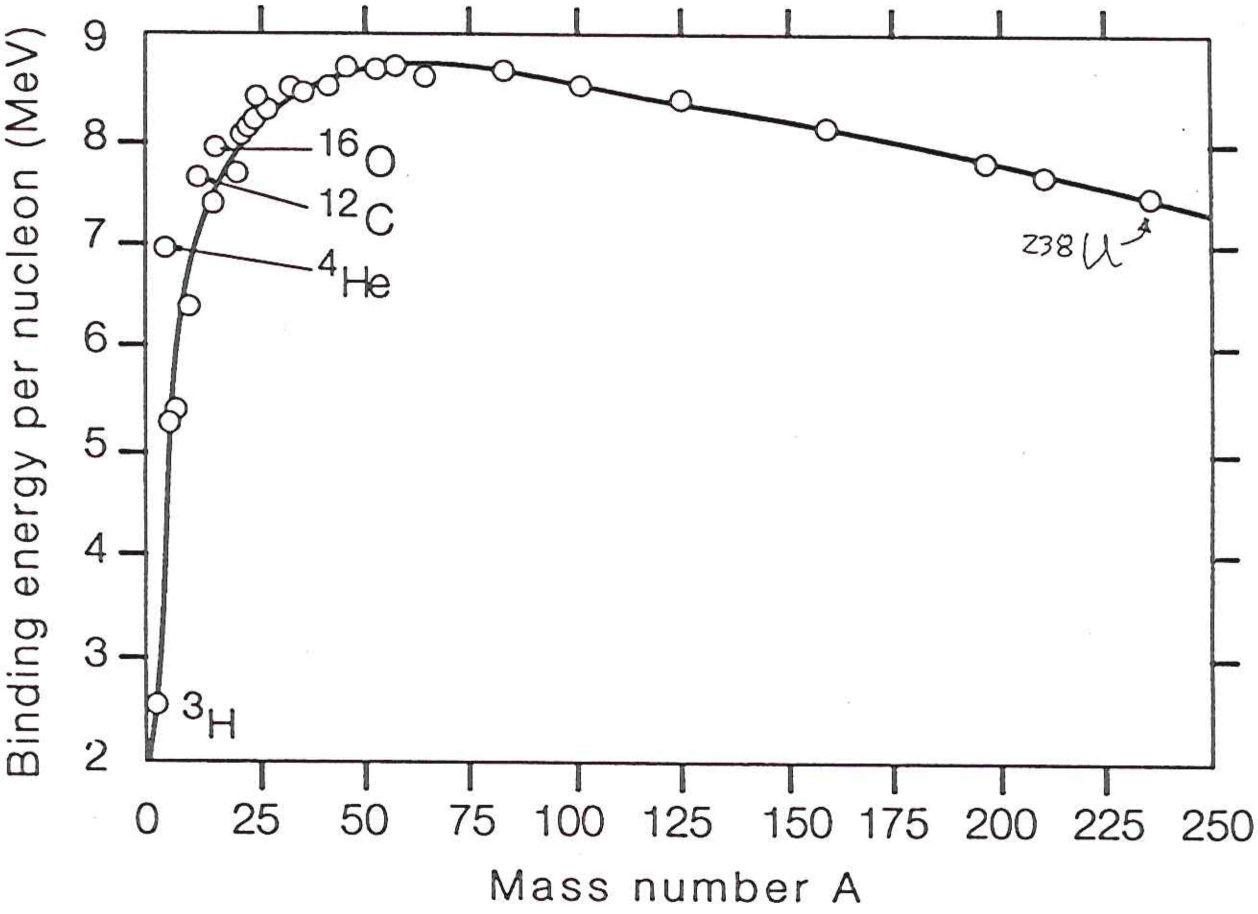


Figure 4.37 Binding energy per nucleon versus the mass number *A* for stable nuclei

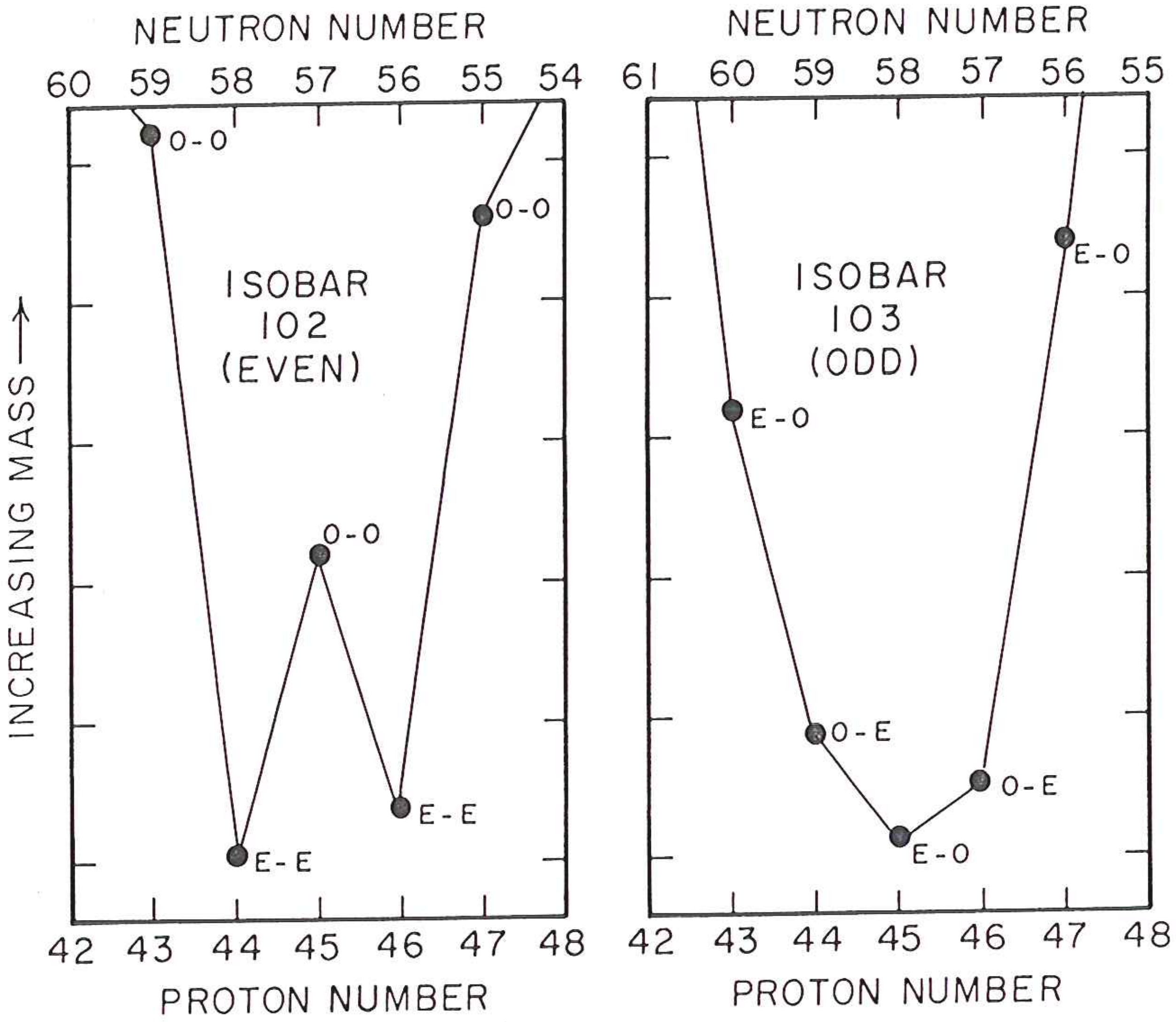
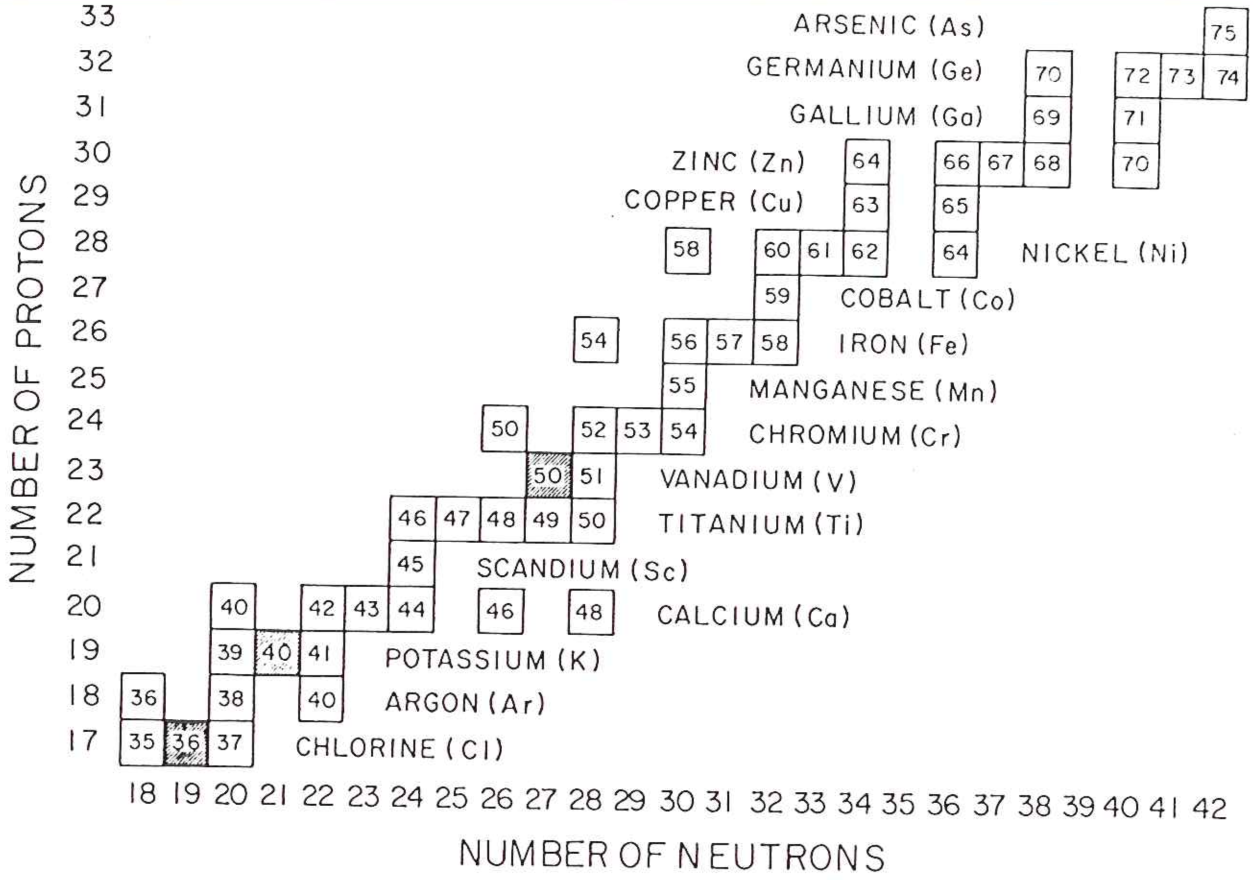
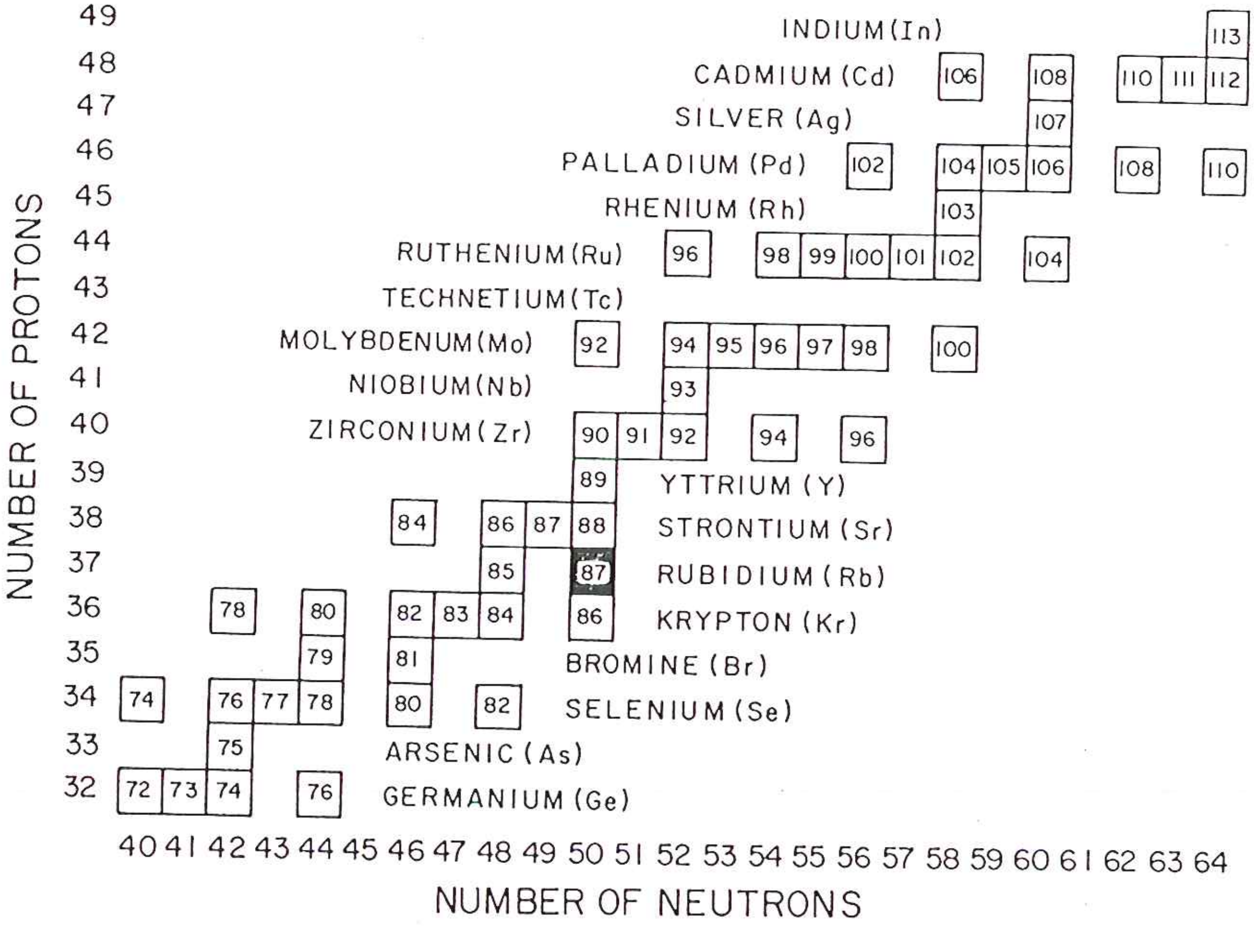


Figure 2-14. Odd–even particle number systematics: Shown here are the masses for two sets of nuclides. On the left are shown nuclides of particle number 102 (an even number). On the right are shown nuclides of particle number 103 (an odd number). The smaller the mass the more strongly the nuclide is bound together. For odd isobars, of the various possible neutron–proton combinations, one always has a lower mass than both its adjacent neighbors. For even isobars, there are usually two such nuclides. The reason for this difference is that odd-odd neturon–proton combinations are less tightly bound than even–even combinations.


NUMBER OF PROTONS
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
ARSENIC (As)
75
GERMANIUM (Ge)
70
72
73
74
GALLIUM (Ga)
69
71
ZINC (Zn)
64
66
67
68
70
COPPER (Cu)
63
65
58
60
61
62
64
NICKEL (Ni)
59
COBALT (Co)
54
56
57
58
IRON (Fe)
55
MANGANESE (Mn)
50
52
53
54
CHROMIUM (Cr)
50
51
VANADIUM (V)
46
47
48
49
50
TITANIUM (Ti)
45
SCANDIUM (Sc)
40
42
43
44
46
48
CALCIUM (Ca)
39
40
41
POTASSIUM (K)
36
38
40
ARGON (Ar)
35
36
37
CHLORINE (Cl)
18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42
NUMBER OF NEUTRONS


NUMBER OF PROTONS
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
INDIUM (In)
113
CADMIUM (Cd)
106
108
110
111
112
SILVER (Ag)
107
PALLADIUM (Pd)
102
104
105
106
108
110
RHENIUM (Rh)
103
RUTHENIUM (Ru)
96
98
99
100
101
102
104
TECHNETIUM (Tc)
MOLYBDENUM (Mo)
92
94
95
96
97
98
100
NIOBIUM (Nb)
93
ZIRCONIUM (Zr)
90
91
92
94
96
89
YTTRIUM (Y)
84
86
87
88
STRONTIUM (Sr)
85
87
RUBIDIUM (Rb)
78
80
82
83
84
86
KRYPTON (Kr)
79
81
BROMINE (Br)
74
76
77
78
80
82
SELENIUM (Se)
75
ARSENIC (As)
72
73
74
76
GERMANIUM (Ge)
40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64
NUMBER OF NEUTRONS

But in general, more even-A than odd-A isotopes ⇒ more abundant

- no stable Tc ($Z = 43$) or Pm ($Z = 61$) — not found on $\oplus$ or in Sun

$$^{97}\text{Tc} \quad (T_{1/2} = 2.6 \text{ m.y.})$$
$$^{98}\text{Tc} \quad (T_{1/2} = 4.2 \text{ m.y.})$$

All decayed since $T = 4.5$ b.y.

<u>But</u> Tc absorption lines seen in supernova explosions

- peaks in abundance at $A \approx 138$ and $A = 208$ — associated with <u>minima</u> in neutron capture cross section — see Fig. 2-11

elements with a low neutron capture probability will tend to "stay put" whereas those with a high capture probability will be transmuted.

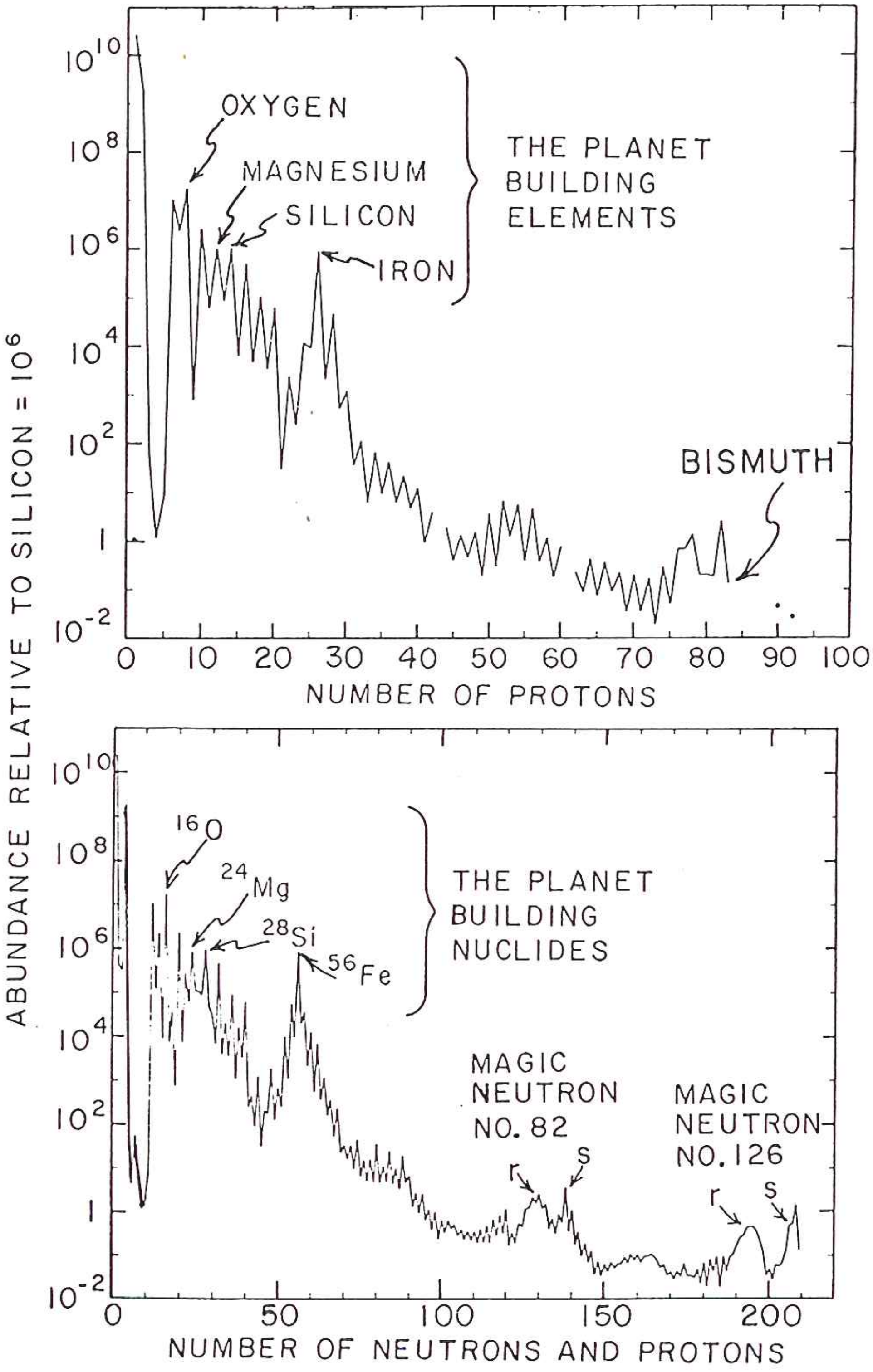


Figure 2-12. The raw material for planet formation: The upper diagram shows the relative abundances of the elements. Up to bismuth there are only two elements not found in nature; technetium (element 43) and promethium (element 61). The lower diagram shows the relative abundance, of the isobars. Only two isobars of nuclear number less than 208 are not represented in nature, those of mass 5 and of mass 8.

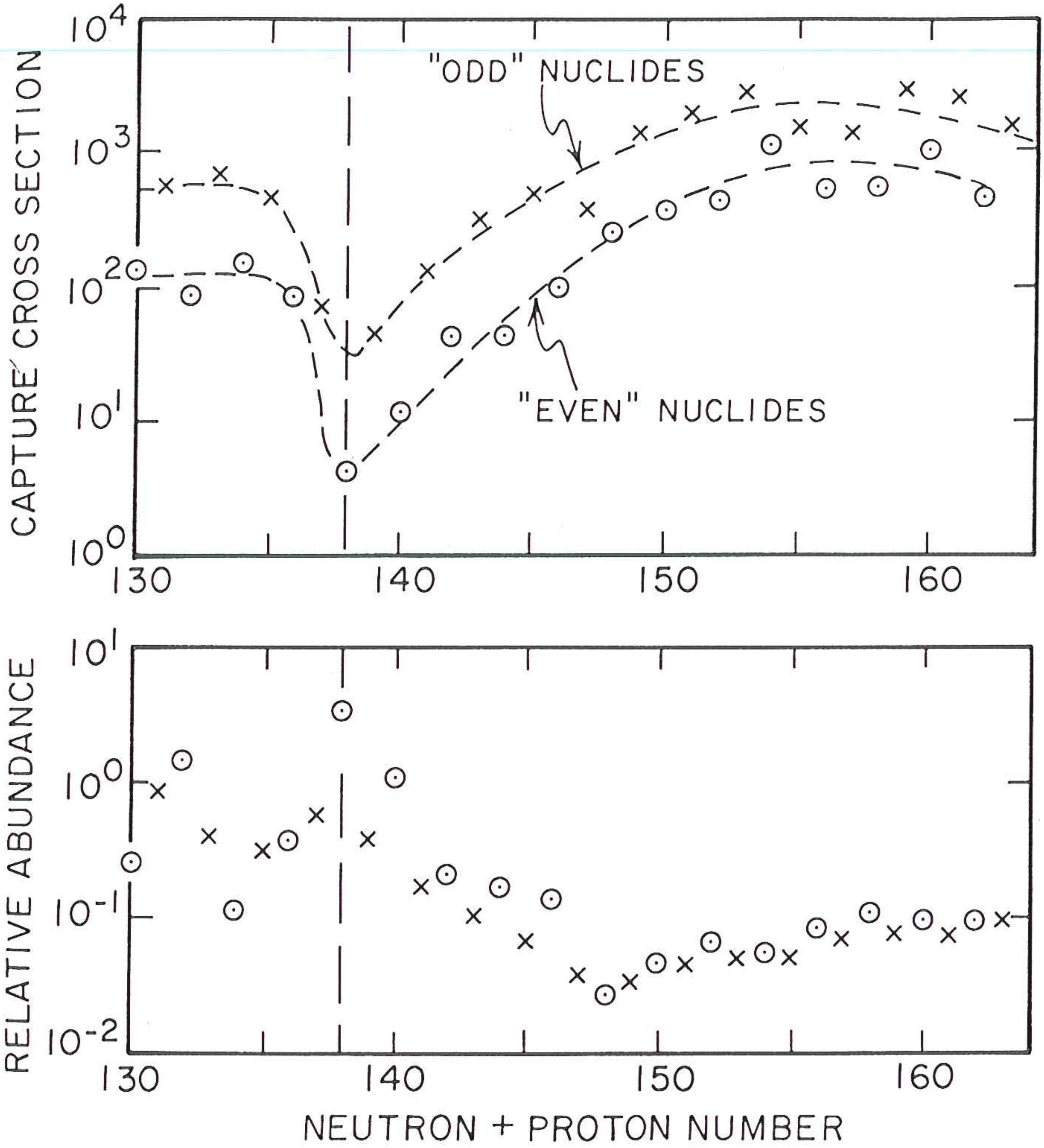


Figure 2-11. The relationship between neutron-capture cross sections and abundance: In the upper panel is shown the neutron-capture cross sections of nuclides produced by the s-process as a function of mass of the nuclide. Note the smoothness of the trend; note also that nuclides with an even number of nuclear particles have lower cross sections than those of their odd-numbered neighbors. Finally, note the minimum in the cross sections for both the even and odd nuclides near mass 138. Nuclides with this and neighboring masses have 82 neutrons, one of the magic numbers (see Fig. 2-6). As can be seen there is an inverse correlation between abundance and cross section. Nuclides with low capture cross section are higher in abundance.

- peaks in abundance at A = multiples of 4 i.e. elements composed of α particles — these elements are particularly <u>stable</u>.

see Table 3-8

The ⊕ and other terrestrial planets are 85% only 4 isotopes

- ^{16}O
- ^{24}Mg
- ^{28}Si
- ^{56}Fe

Conclude with Broecker's discussion of his Table 3-7 — <u>why</u> are these the only 4 elements present in the earth

Elements that are <u>volatile</u> — i.e. that do not form stable compounds at high T — are lost during the accretion process

volatile in gaseous form O_2 but...

Oxygen — can bind to metals in silicates e.g. $MgSiO_3$ or to H in H_2O

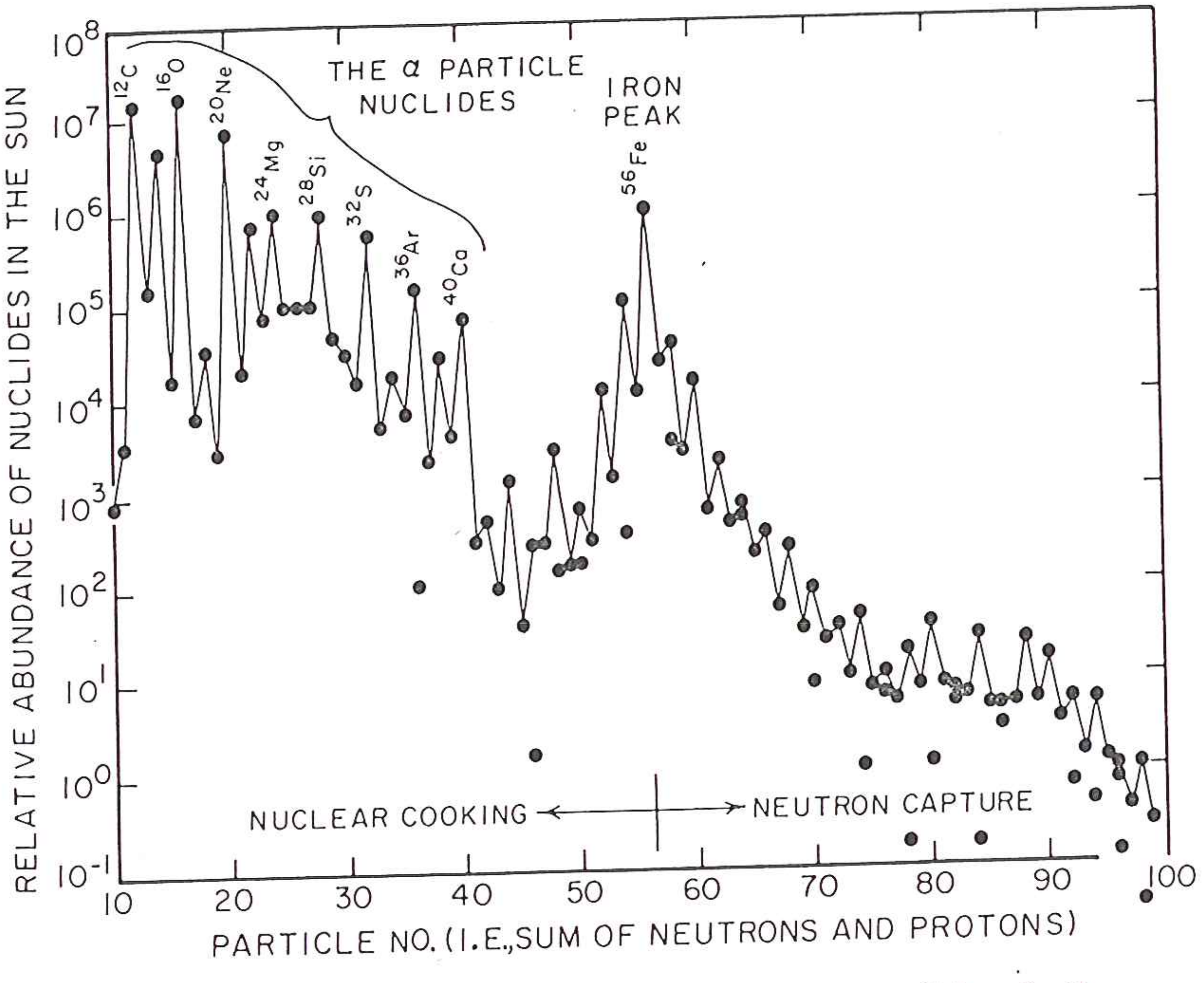


Figure 2-10. Relative abundances of individual nuclides: In the mass range 10 to 50, nuclides with particle numbers divisible by 4 (i.e., 12, 16, 20, 24, 28, 32 . . .) have abundances far above those of their neighbors. They are referred to as the *α*-particle nuclides. In the particle number range 50 to 100 the abundances of nuclides with an even particle number stand about a factor of 3 above those for their odd-numbered neighbors. Where more than one point is shown at a given mass number, two different nuclides with the same neutron-plus-proton number exist.

Table 3-8. Isotopic abundances of the big four planet-producing elements:* Note that for three of the elements the dominant isotope has a nucleus consisting of an integral number of *α*-particles (i.e., four in ^{16}O, six in $^{24}M_6$, seven in ^{28}Si). The terrestrial planets are 85 percent by weight ^{16}O, ^{24}Mg, ^{28}Si, and ^{56}Fe!

OXYGEN (8 protons)	^{16}O	^{17}O	^{18}O	
	99.76%	0.04%	0.20%	
MAGNESIUM (12 protons)	^{24}Mg	^{25}Mg	^{26}Mg	
	78.99%	10.00%	11.01%	
SILICON (14 protons)	^{28}Si	^{29}Si	^{30}Si	
	92.23%	4.67%	3.10%	
IRON (26 protons)	^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe
	5.8%	91.8%	2.1%	0.3%

---

*In reading the lines in solar rainbows we get estimates of the abundances of elements. Many elements have more than one isotope. Thus the solar evidence must be supplemented if we are to get the abundances of individual isotopes. This is done by measuring the ratios of the isotopes of a given element in meteorites or Earth surface materials. Although separations among the elements have caused large biases in the chemical composition of Earth surface rocks, these separations do not extend to the isotopes of a given element. The isotopes of an element are nearly chemically identical. Thus, the isotopic composition of a given element is generally found to be the same whether the sample analyzed is from the Earth or from a meteorite.

Table 3-7. Relative abundance of the first 28 elements and their fates during the formation of the terrestrial planets:

Element Number	Element Name	Compound Solid	Compound Gas	Rel. Abundance In Sun*	Fate†	Rel. Abundance In Chondrites*
1	HYDROGEN		H_2	40,000,000,000	(1)	—
2	HELIUM		He	3,000,000,000	(1)	trace
3	LITHIUM	Li_2O		60	(3)	50
4	BERYLLIUM	BeO		1	(3)	1
5	BORON	B_2O_3		43	(2)	6
6	CARBON		CH_4	15,000,000	(1)	2,000
7	NITROGEN		NH_3	4,900,000	(1)	50,000
8	OXYGEN		H_2O**	18,000,000	(2)	3,700,000
9	FLUORINE		HF	2,800	(1)	700
10	NEON		Ne	7,600,000	(1)	trace
11	SODIUM	Na_2O		67,000	(2)	46,000
12	MAGNESIUM	MgO		1,200,000	(3)	940,000
13	ALUMINUM	Al_2O_3		100,000	(3)	60,000
14	SILICON	SiO_2		1,000,000	(3)	1,000,000
15	PHOSPHORUS	P_2O_5		15,000	(3)	13,000
16	SULFUR	FeS	H_2S	580,000	(2)	110,000
17	CHLORINE		HCl	8,900	(1)	700
18	ARGON		Ar	150,000	(1)	trace
19	POTASSIUM	K_2O		4,400	(2)	3,500
20	CALCIUM	CaO		73,000	(3)	49,000
21	SCANDIUM	Sc_2O_3		41	(3)	30
22	TITANIUM	TiO_2		3,200	(3)	2,600
23	VANADIUM	VO_2		310	(3)	200
24	CHROMIUM	CrO_2		15,000	(3)	13,000
25	MANGANESE	MnO		11,000	(3)	9,300
26	IRON	FeO,FeS,Fe		1,000,000	(3)	690,000
27	COBAL	CoO		2,700	(3)	2,200
28	NICKEL	NiO		58,000	(3)	49,000

why Al so low?
no stable α-particle nuclide ⇒
28 Al is unstable

why? ⇒ 100,000

*Relative to 1,000,000 silicon atoms.
†(1) Highly volatile; mainly lost;
(2) Moderately volatile; partly captured;
(3) Very low volatility; largely captured.
**Plus metal oxides.

Let us run through the list of elements in Table 3-7 and see why planets might be dominated by as few as four elements. The first element on the list is hydrogen. In the cloud of gas plus dust from which the planets formed, hydrogen atoms were present either as hydrogen gas (H_2) or as gases of carbon (CH_4), of nitrogen (NH_3), or of oxygen (H_2O). The Earth and its fellow terrestrial planets trapped only a tiny fraction of these gases; the rest was lost.

Helium exists only as a gas. Like the other noble gases, it seldom makes chemical unions with other elements. Hence virtually all the helium was lost. Even the very small amount of helium we do find today in the Earth's atmosphere and in gases escaping from the Earth's interior was not captured by the Earth; rather, it was produced within the Earth by the radioactive decay of the elements uranium and thorium.

The next three elements—lithium, beryllium, and boron—were produced in very small abundance by the synthesis mechanisms in stars. Their abundance relative to other solid-prone elements like magnesium, silicon, and iron is too small to permit them to be major constituents of the planets.

Carbon and nitrogen, in the presence of the large amounts of hydrogen gas in the planetary nebula, would have been in the form of methane (CH_4) and ammonia (NH_3). These gaseous compounds were largely lost.

While also attracted to chemical unions with hydrogen, the element oxygen is even more strongly attracted to chemical unions with the elements chemists refer to as metals. In the cloud from which the Sun and the planets formed there were five times as many oxygen atoms as all metal atoms taken together; hence, only about 20 percent of the available oxygen atoms were able to get the metal atoms that would be their first choice as chemical mates. The remainder had to take their second chemical choice—hydrogen atoms. The gaseous water molecules thus formed were largely swept away. Only those oxygens with metal-atom mates were incorporated into solid phases.

After oxygen on the list in Table 3-7 come fluorine and neon. Fluorine atoms have a strong tendency to combine with hydrogen in the form of hydrofluoric acid (HF). Under the conditions that prevailed when the planets formed, HF was likely to be a gas. Like helium, neon shuns chemical unions. Hence, both elements were largely driven away.

So far we have gone through ten elements. Of these, six (hydrogen, helium, carbon, nitrogen, fluorine, and neon) formed gases and were largely lost. Three others (lithium, boron, and beryllium) had such small abundances as to be unimportant to the bulk composition of planetary material. Only oxygen was sufficiently abundant and sufficiently prone toward the formation of solid phases to become a major contributor to the terrestrial planets.

The next five elements on the list are all metals that prefer chemical unions with oxygen. Four of them (magnesium, aluminum, silicon, and phosphorus) were efficiently trapped in the solid material. The fifth (sodium) is moderately volatile; hence, some was lost. As can be seen in Table 3-8, silicon and magnesium both have isotopes that have nuclear-particle numbers divisible by four (^{24}Mg and ^{28}Si). These so-called alpha-particle nuclides were produced in stars in greater abundance than were neighboring nuclides. For this reason, magnesium and silicon are more abundant than sodium, aluminum, and phosphorus, which have no isotopes of the alpha-particle variety.

Next on the list is sulfur. Its situation is akin to that for oxygen. On one hand, it could form the hydrogen-bearing gas H_2S. On the other, it could combine with iron to form a solid, FeS. Our evidence from meteorites suggests that a significant fraction of the available sulfur was captured (as FeS).

The next two elements on the list, chlorine and argon, were largely lost as gases. Chlorine was in the form of hydrochloric acid (HCl), a gas. Argon, like helium and neon, is a noble gas which shuns chemical unions.

Next on the list are two more metallic elements, potassium and calcium. Calcium in the oxide form has a very low volatility. Like sodium, potassium is moderately volatile and hence was not captured with the same efficiency as were metals of low volatility. Despite its low abundance, potassium has an important role in Earth studies. In part because one of its isotopes (^{40}K) is radioactive and in part because it is a very important constituent of the Earth's crust.

So we see that in the second group of ten elements, five (magnesium, aluminum, silicon, phosphorus, and calcium) were largely captured. Three (sodium, potassium, and sulfur) were partly captured. Two (chlorine and argon) were largely lost.

Between calcium and iron there is a big sag in the abundance curve. Thus, although most of the elements in this interval are metals of low volatility, none is sufficiently abundant to challenge silicon or magnesium.

The abundance of iron, the ultimate product of nuclear fires, stands well above that of its neighboring elements. Also, none of its chemical forms in the early solar system was particularly volatile. As its abundance is similar to that of magnesium and silicon, it became one of the "big four" elements in the terrestrial planets.

Beyond iron, the abundance of the elements drops rapidly with increasing proton number. Only nickel is sufficiently abundant to be important. As shown in Table 3-5, nickel along with aluminum, calcium, and sodium make up the second abundance group.

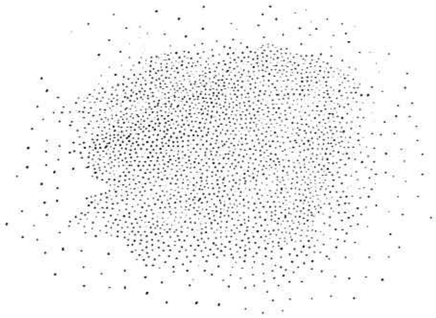
Thus we see that a combination of nuclear physics (which sets the relative abundances of the elements) and inorganic chemistry (which sets the chemical form of the elements in the planetary nebula) dictated that rocky planets like Earth consist primarily of the elements oxygen, magnesium, silicon, and iron. One might then ask why the ratio of Mg to Si to Fe is not identical in the terrestrial planets. The answer must be that at some stage in the planet-formation process, the material must have been so hot that even iron, magnesium, and silicon were at least in part in volatile form and hence lost from the solar nebula along with the other gases. This partial loss separated these elements from one another. The chemical differences among the planets tell us that the nature and extent of this separation must have varied from place to place in the solar nebula.

1/5 of O in Sun found in chondrites and $\oplus$ — almost all of remaining 4/5 lost — some in oceans and ground water

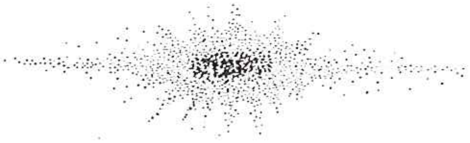
Fe is one of the big four rather than, say, K or Ca, simply because it is so abundant in the Sun.

We also understand, in a general way, the reasons for the differences among planets

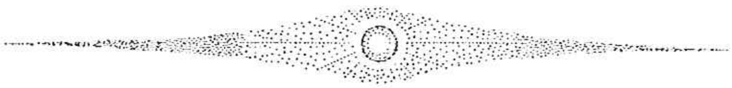
- Figs. 2.6 & 2.8 Cox shows process of solar system formation
- accretion disk hotter near Sun $\Rightarrow$ more volatiles driven off
- Mercury $\rho \approx 5500$ kg/m^3 $\approx \rho_\oplus$ but smaller — very little correction for compression — much larger Fe core — ~~consistent~~ $X_{Fe} \approx 0.4$
  $R_{core} = 0.75\, R_{Mercury}$



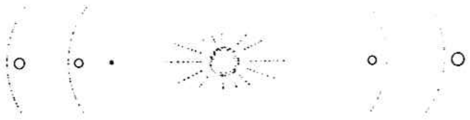
(A) **A slowly rotating portion of a large nebula** becomes a distinct globule as a mostly gaseous cloud collapses by gravitational attraction.



(B) **Rotation of the cloud prevents collapse of the equatorial disk** while a dense central mass forms.



(C) **A protostar "ignites"** and warms the inner part of the nebula, possibly vaporizing preexisting dust. As the nebula cools, condensation produces solid grains that settle to the central plane of the nebula.



(D) **The dusty nebula clears** either by dust aggregation into larger particles (planets or planetesimals) or by ejection during a T-Tauri stage of the star's evolution. A star energized by fusion and a system of cold bodies remains. Gravitational accretion of these small bodies eventually leads to the development of a small number of major planets.

Figure 2.6

The evolution of a dusty nebula with a surrounding system of orbiting planets is shown in this schematic diagram.

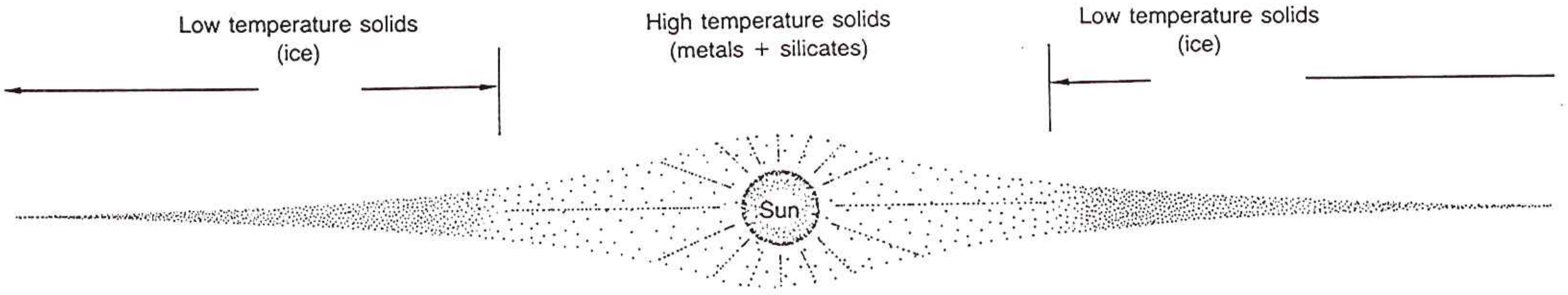


Figure 2.8

A cross section of a hypothetical nebula shows a star forming in its center. Condensation of solids from a solar nebula with a temperature gradient may have given rise to compositional differences in the condensates. At one instant, the condensates in the inner part of the developing solar system would consist of high temperature materials such as silicates, while at the same instant, but farther from the Sun, the nebula may have been cool enough to allow ices to be fully condensed as well. Since water was relatively abundant in the nebular gases, more solid matter formed in the cooler outer part of the nebula.

Giant outer planets mostly
H and He

Their moons have thick outer
layers of ice (CH_4 , NH_3 , H_2O)

See Fig. 2.9

History of element formation summarized
in Fig 4-7 Broecker

Took awhile after big bang for
stars to begin to form

Our sun formed 4.5 b.y. ago — has
not received any new elements since.

Table 3-3. Characteristics of the planets:*

Planet Name	Radius 10^8 cm	Volume 10^{26} cm^3	Mass 10^{27} gm	Density gm/cm^3	Corrected density† gm/cm^3
Mercury	2.44	0.61	0.33	5.42	5.4
Venus	6.05	9.3	4.9	5.25	4.3
Earth	6.38	10.9	6.0	5.52	4.3
Mars	3.40	1.6	0.64	3.94	3.7
Jupiter	71.90	15,560	1900	1.31	<1.3
Saturn	60.20	9130	570	0.69	<0.7
Uranus	25.40	690	88	1.31	<1.3
Neptune	24.75	635	103	1.67	<1.7
Pluto	1.6	0.17	?	?	?

*The mass of the Sun is 1.99×10^{33}gm, 1000 times the mass of Jupiter.
†Density a planet would have in the absence of gravitational squeezing.

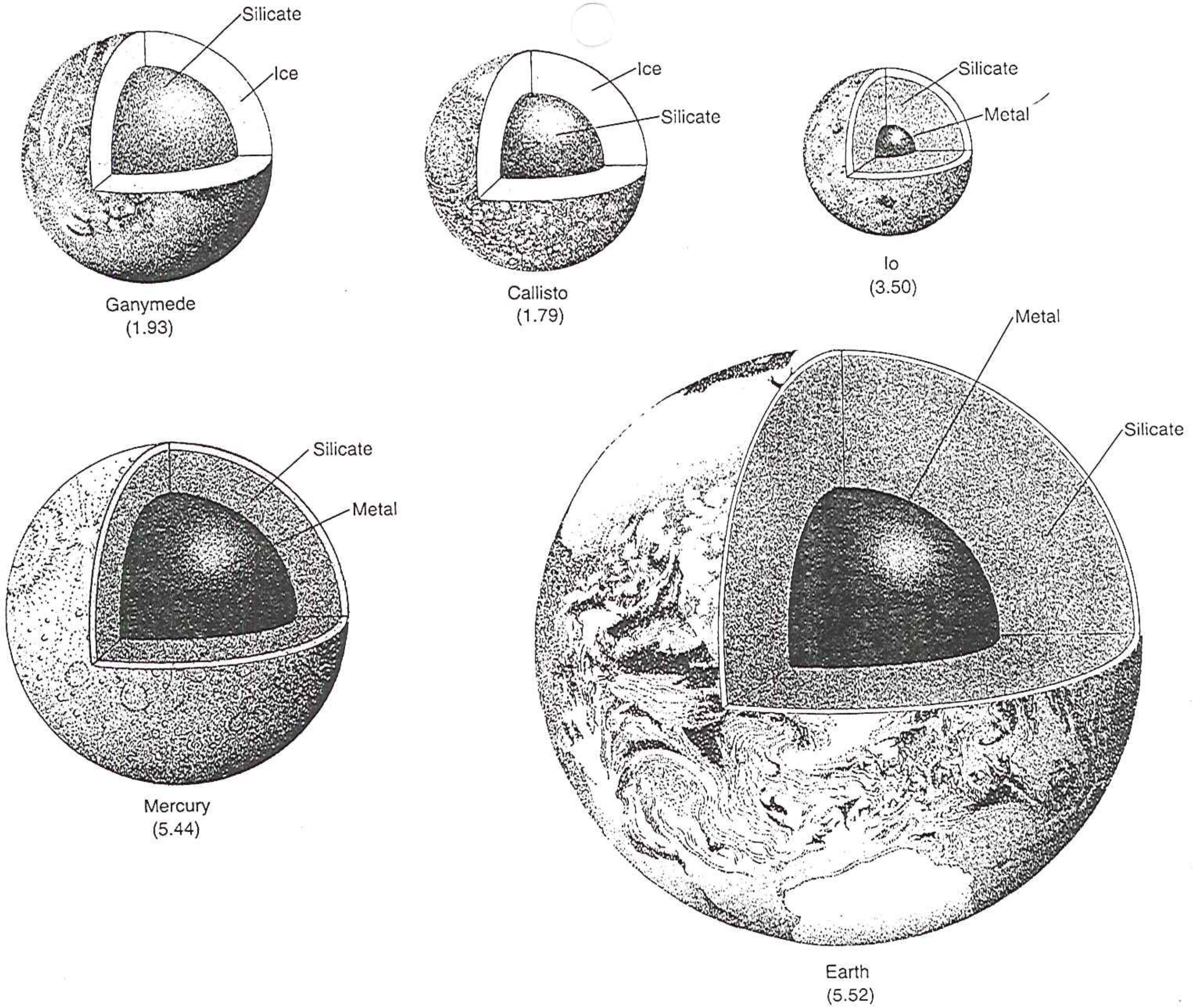
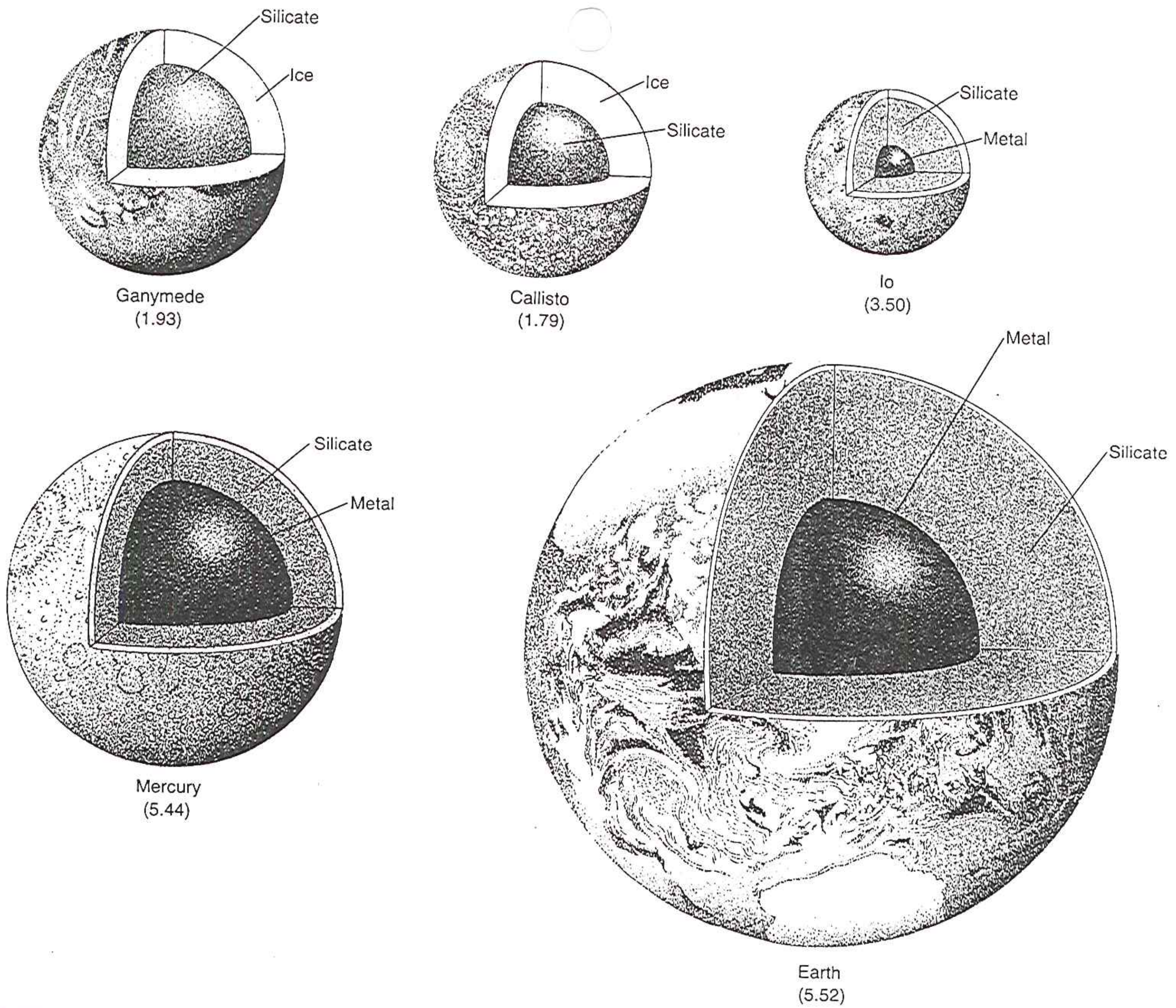


Figure 2.9

The interiors of five planets are compared in this diagram, which illustrates the relative size of various internal components. The densities of the bodies are also given in g/cm^3. Although some scientists believe these layered structures are the result of layer by layer accretion from the nebula, there is good evidence to suggest that the planets were originally relatively homogeneous and that the layered internal structures are the result of planetary differentiation. Note how the proportions of silicate, ice, and metal change from bodies in the inner solar system to those in the outer solar system.

Table 3-10. Densities and melting temperature of possible planet-forming solids:

Compound	Number of nuclear particles per atom	Density of solid gm/cm^3	Melting point of solid °C
		ICES	
CH_4	3.2	0.4	−184
NH_3	4.2	0.7	−78
H_2O	6.0	1.0	0
		OXIDES	
SiO_2	20	2.7	1710
Mg_2SiO_4	20	3.2	1200
		METAL	
Fe	56	7.9	1540



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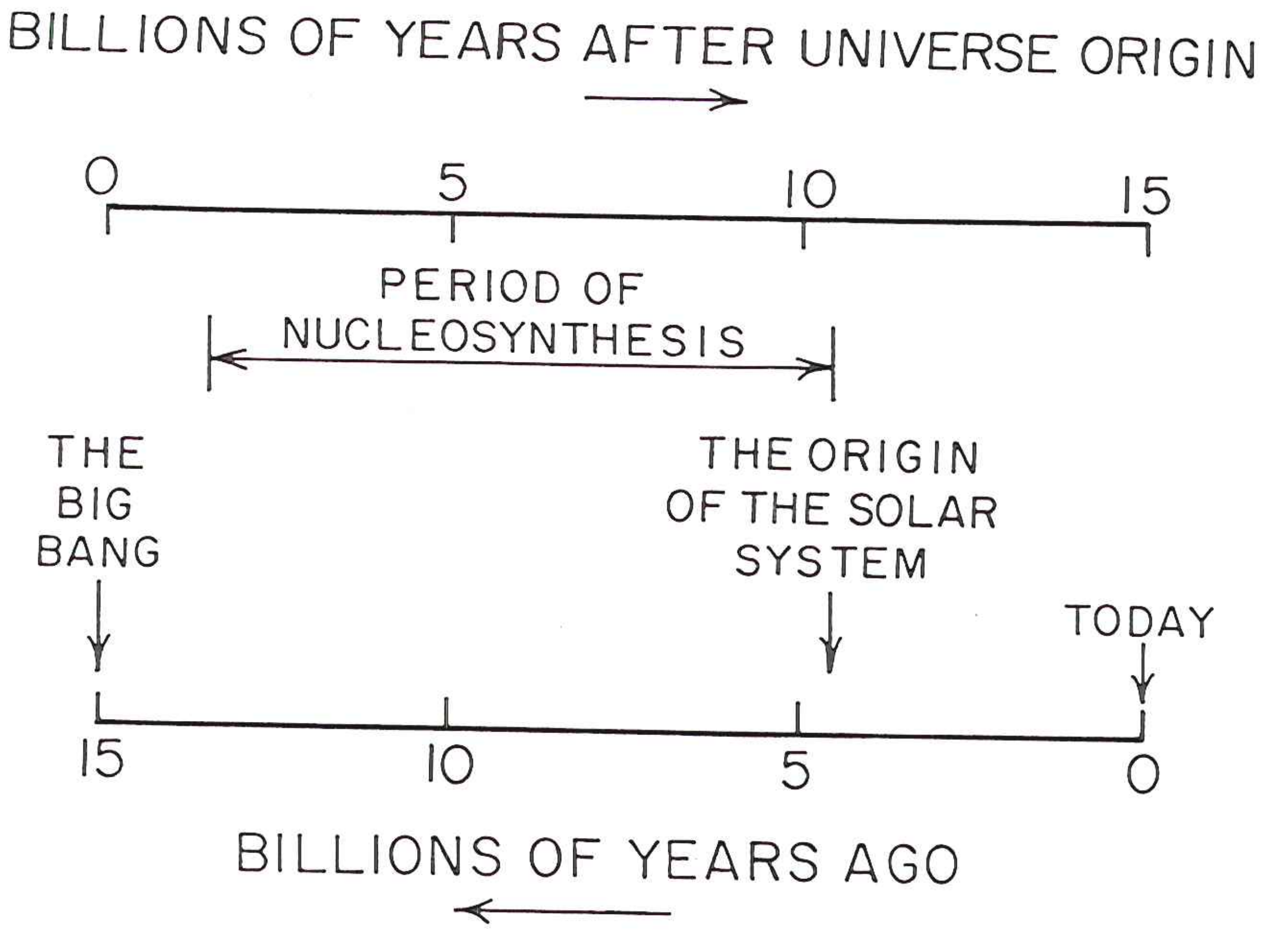


Figure 4-7. Summary of the chronology of universe events: The period of nucleosynthesis refers to the time interval over which the elements heavier than hydrogen and helium that are found in our solar system were produced. For the galaxy as a whole the period of nucleosynthesis extends right up to the present. The matter in the solar system was isolated from the galaxy 4.6 billion years ago.

extra from here on

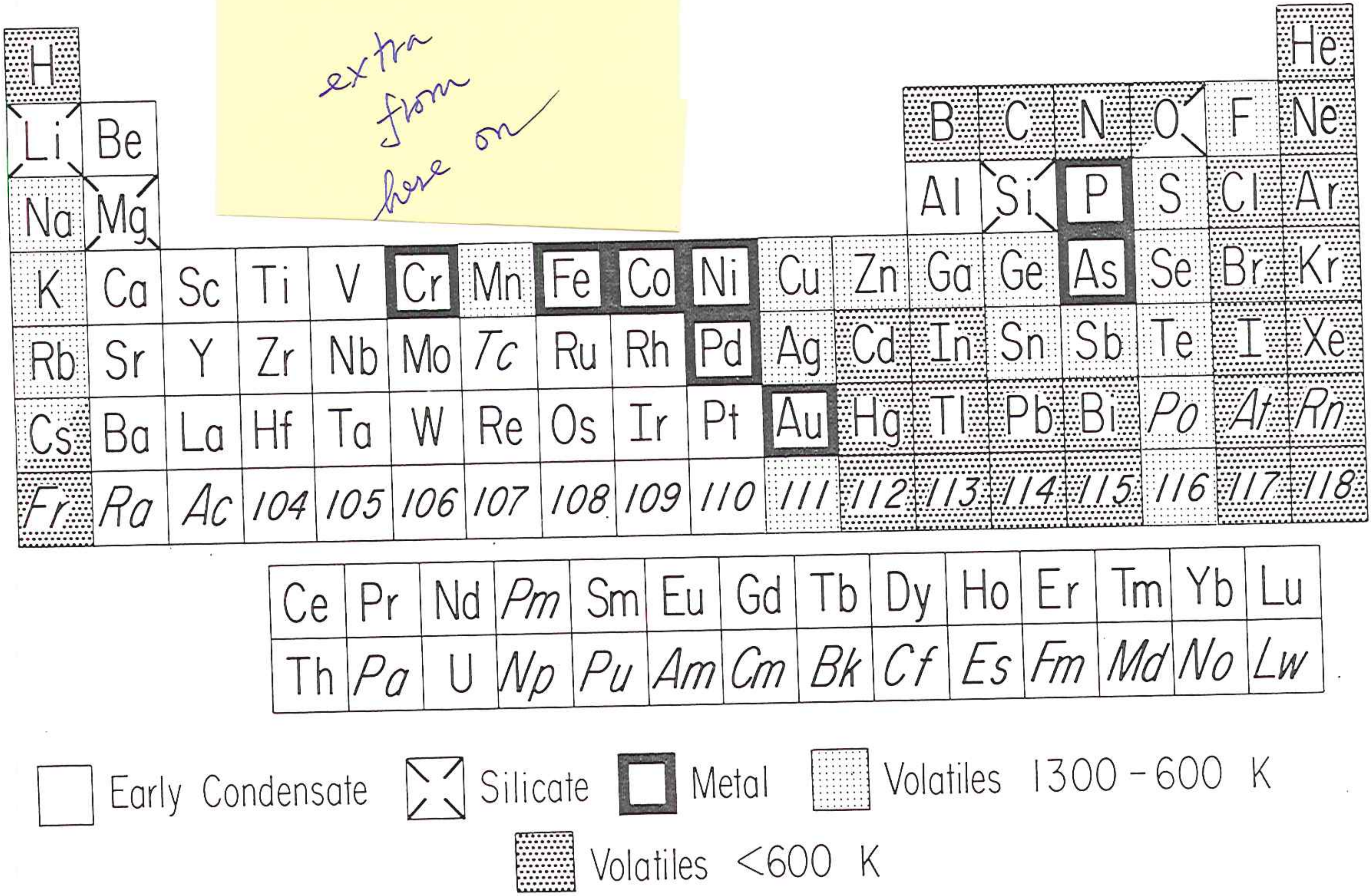
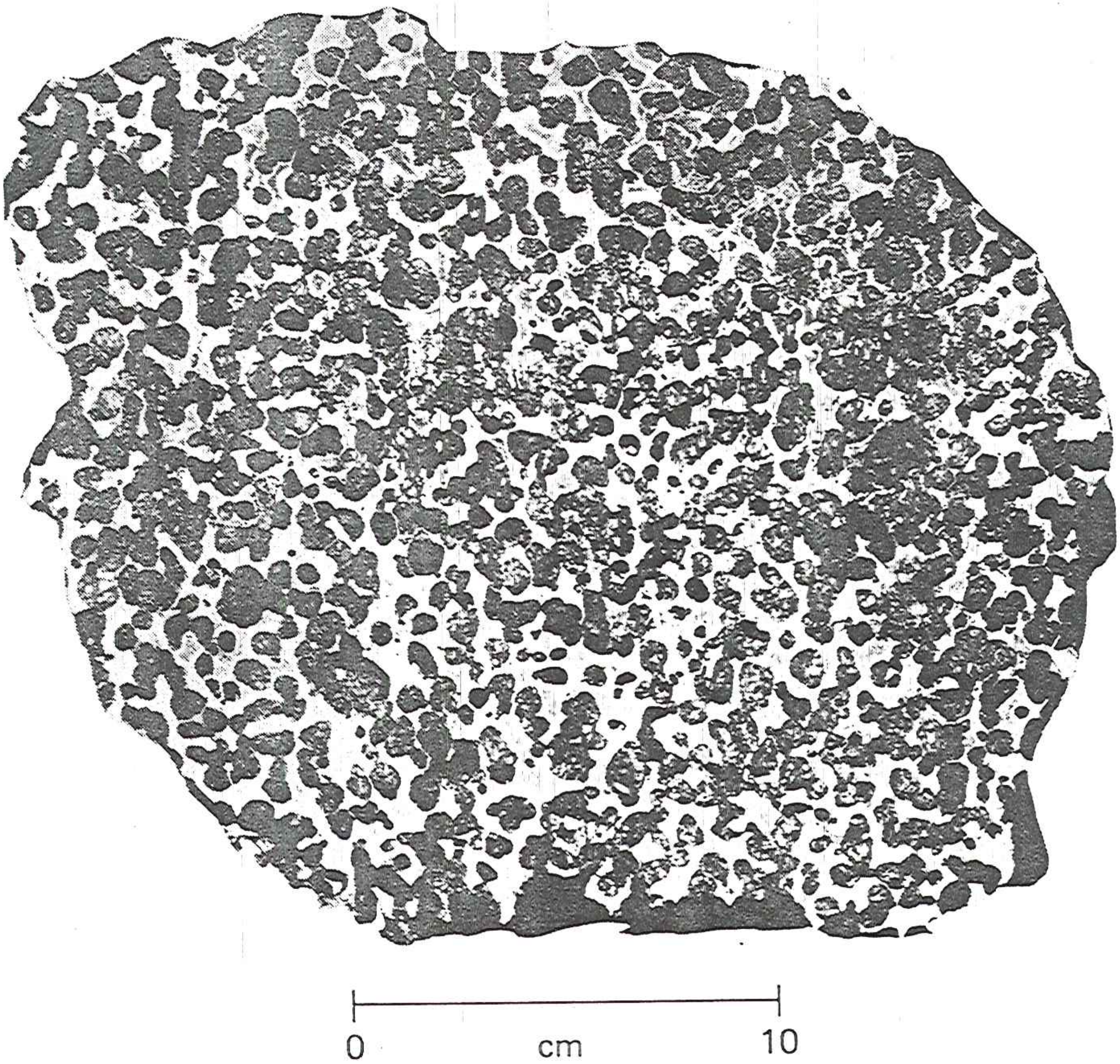


FIGURE 1-5
Condensation behavior of the elements. Short-lived radioactive elements are shown in italics (after Morgan and Anders, 1980).

FIG. 5-11 Polished slab of a pallasitic (stony-iron) portion of the Brenham (Kansas) meteorite. Coarse, rounded crystals of olivine are embedded in massive nickel–iron metal (white by reflected light). Photograph courtesy of the American Museum of Natural History.



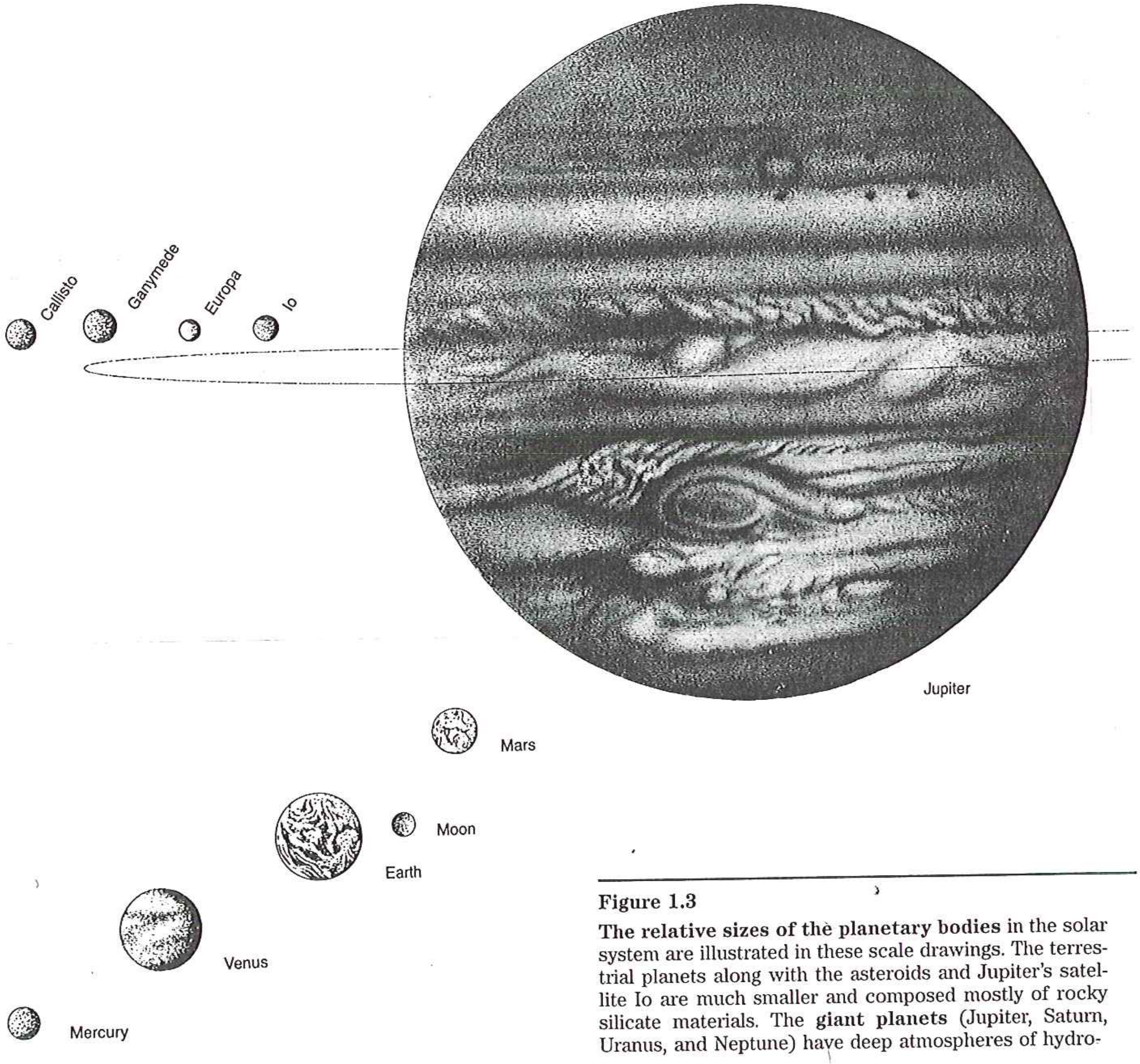
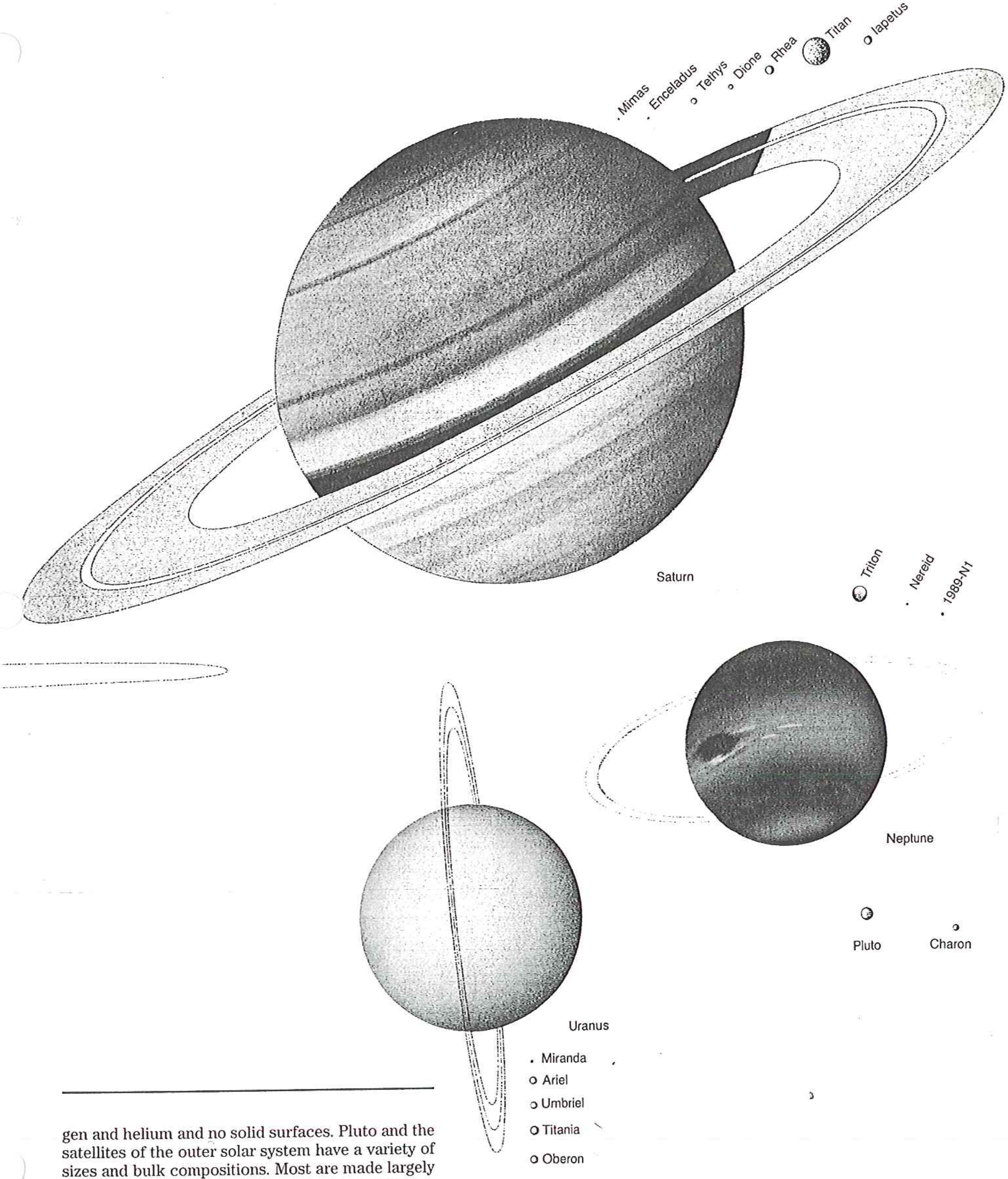


Figure 1.3

The relative sizes of the planetary bodies in the solar system are illustrated in these scale drawings. The terrestrial planets along with the asteroids and Jupiter's satellite Io are much smaller and composed mostly of rocky silicate materials. The **giant planets** (Jupiter, Saturn, Uranus, and Neptune) have deep atmospheres of hydro-



gen and helium and no solid surfaces. Pluto and the satellites of the outer solar system have a variety of sizes and bulk compositions. Most are made largely of water ice, but some also have atmospheres (Titan, Triton), and others are so cold that they have methane ice or nitrogen ice at their surfaces.

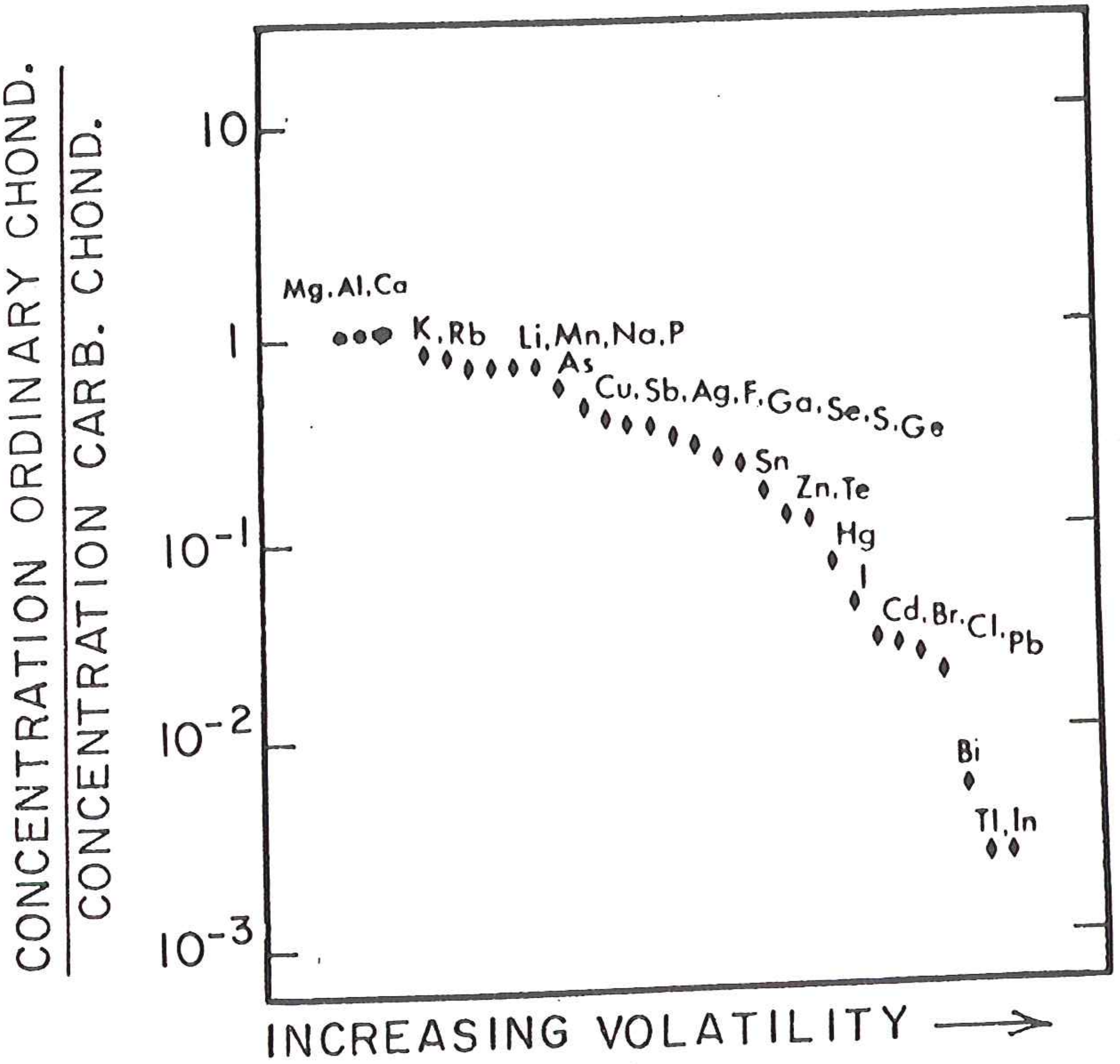


Figure 3-6. Depletion of volatile elements in ordinary chondrites: For each element the ratio of its concentration in ordinary chondrites to that in carbonaceous chondrites is shown. While the exact order of the elements with regard to volatility is subject to interpretation to a large extent, the greater the volatility of an element, the greater the degree to which it was lost during the baking process.

Table 3-6. Comparison between the chemical compositions of various meteorite classes and that of the bulk Earth: Despite the great change in the fraction of iron in oxide form from class to class (see last column), the relative abundances of the three major constituent metals (i.e., Si, Mg, and Fe) remain nearly unchanged in the high-iron chondrites. As can be seen, the Earth is richer in magnesium and iron relative to silicon than are meteorites.

	Fraction of mass as SiO_2, MgO, FeO, and iron metal*	Relative atom abundance				Relative mass abundance				Fraction of iron in oxide form
		Si	Mg	Fe	O†	Si	Mg	Fe	O†	
LOW-IRON CHONDRITES										
Enstatite chondrites	.92	100	92	60	325	100	80	119	185	.55
HIGH-IRON CHONDRITES										
Carbonaceous chondrites	.78	100	104	84	380	100	90	167	216	.90
Olivine-Pigeonite chondrites	.92	100	101	78	357	100	87	155	203	.72
Olivine-bronzite chondrites	.91	100	96	79	340	100	83	157	194	.56
Olivine-Hypersthene chondrites	.92	100	84	82	285	100	73	163	162	.01
WHOLE EARTH										
Whole Earth	.94	100	131	126	359	100	114	250	199	.11

---

*FeS present in meteorites included with iron metal.

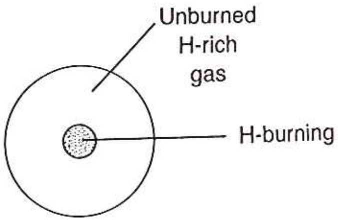
†Excludes oxygen associated with metals other than silicon, magnesium, and iron.

Table 3-11. Approximate compositions of the objects in the solar system: Note that the Sun's mass is nearly 770 times that of the combined planets. The environment in the region of the major planets was sufficiently cold when they formed so that they accumulated ices as well as silicate and iron. These four planets became sufficiently massive to pull in the noncondensible gases H_2 and He.

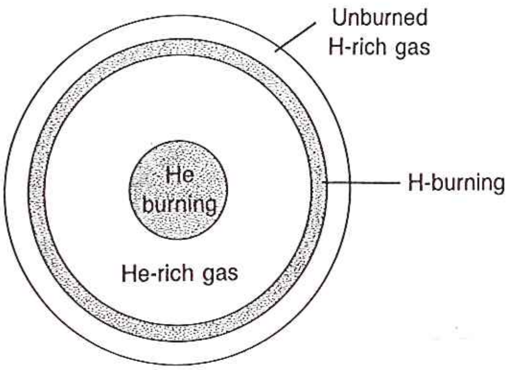
Object	Total Matter	Metals† Fe, Ni, . . .		Oxides† SiO_2, MgO, FeO, . . .		Ices† H_2O, CH_4, NH_4, H_2S, . . .		Gases H_2 + He	
	Mass 10^{27}gm	%	Mass 10^{27}gm	%	Mass 10^{27}gm	%	Mass 10^{24}gm	%	10^{27}gm
Sun	1,990,000	0.1	—	0.2	—	1.2	—	98.5	—
Mercury	0.33	50	0.16	50	0.17	—	—	—	—
Venus	4.87	30	1.46	69	3.36	≈1*	≈0.05*	—	—
Earth	5.97	29	1.73	69	4.12	≈2*	≈0.12*	—	—
Mars	0.64	10	0.06	90	—	—	—	—	—
Asteroids	0.0002	15	0.00003	85	0.00017	—	—	—	—
Jupiter	1900	≈4	≈80	≈9	≈170	≈5	≈100	≈82	≈1550
Saturn	570	≈7	≈40	≈14	≈80	≈12	≈70	≈67	≈380
Uranus	88	≈8	≈7	≈17	≈15	≈60	≈53	≈15	≈13
Neptune	103	≈6	≈6	≈14	≈14	≈70	≈73	≈10	≈10

†Likely as solid forms when accumulated by the planets. In the Sun the temperatures are so high that all elements are in gaseous form.

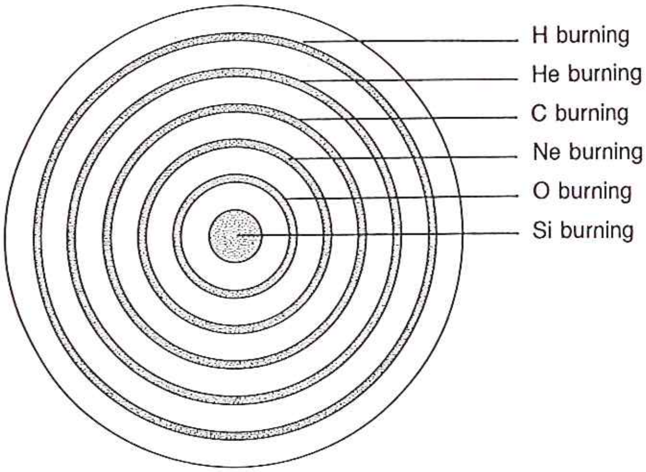
*Likely to have accumulated in some non-ice form.



(A) **The interior of a small star** (less than about 4 times the Sun's mass) changes as it evolves from a small hydrogen-burning star to a large hydrogen- and helium-burning star.



(B) **Small stars burning hydrogen and helium** become cooler at their surfaces and redder and consequently are called red giants. These giants may be 10 to 20 times the diameter of their precursor. Note how the hydrogen-burning shell (shaded) has expanded outward, leaving in its wake a helium-rich shell; eventually hydrogen-burning may extend to the surface causing the disruption of the star's surface and produce a **planetary nebula.**



(C) **The internal structure of a massive star** which has evolved past a helium-burning stage. Concentrically arranged shells where burning takes place (shaded) at progressively higher temperatures are separated by unreactive shells (light) where the material is depleted in the fuel being burned in the outer shell and is too cool to participate in the burning reaction of the next inner shell. The "death" of such a massive star is marked by the production of a nova or supernova.

Figure 2.3

The internal structures of stars change with their age and size or mass.

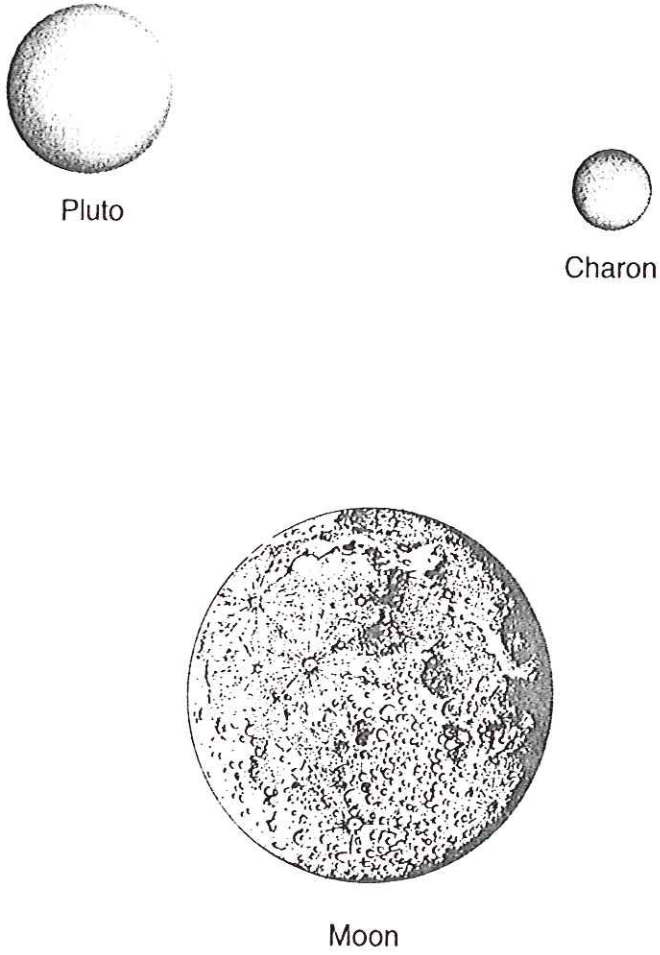


Figure 1.14

Pluto, the smallest planet, and its satellite, Charon, form a double-planet system on the extreme outer edge of the solar system. Charon may be as large as one-half the diameter of Pluto. Both bodies have considerable amounts of methane ice at their surfaces and are more like the icy moons of the outer planets than they are like the gas giants.

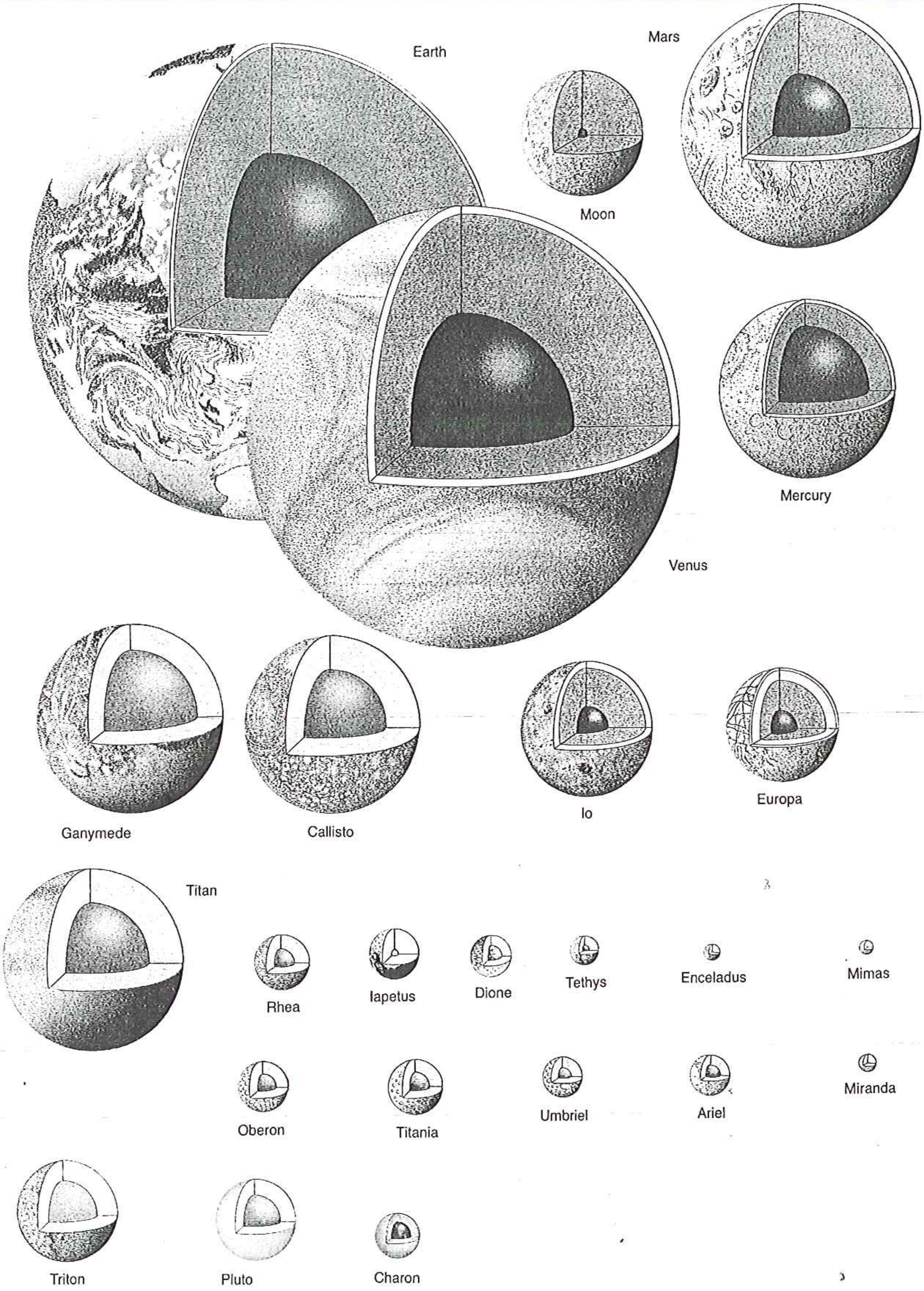


Figure 15.2

The internal structures of the planets and moons are dominated by concentric layers of diverse compositions and mechanical properties. The inner planets and Io probably have dense cores of iron metal and thick mantles and crusts of silicates. In contrast, the other moons of the outer planets and Pluto may have cores of silicates surrounded by mantles of water ice. Although internal differentiation was an important result of accretionary heating in many planets, moons, and asteroids, some small icy satellites of Saturn, Uranus, and Neptune may not be differentiated. The interiors of these small objects may consist of more-or-less homogeneous mixtures of ice and silicate rock.

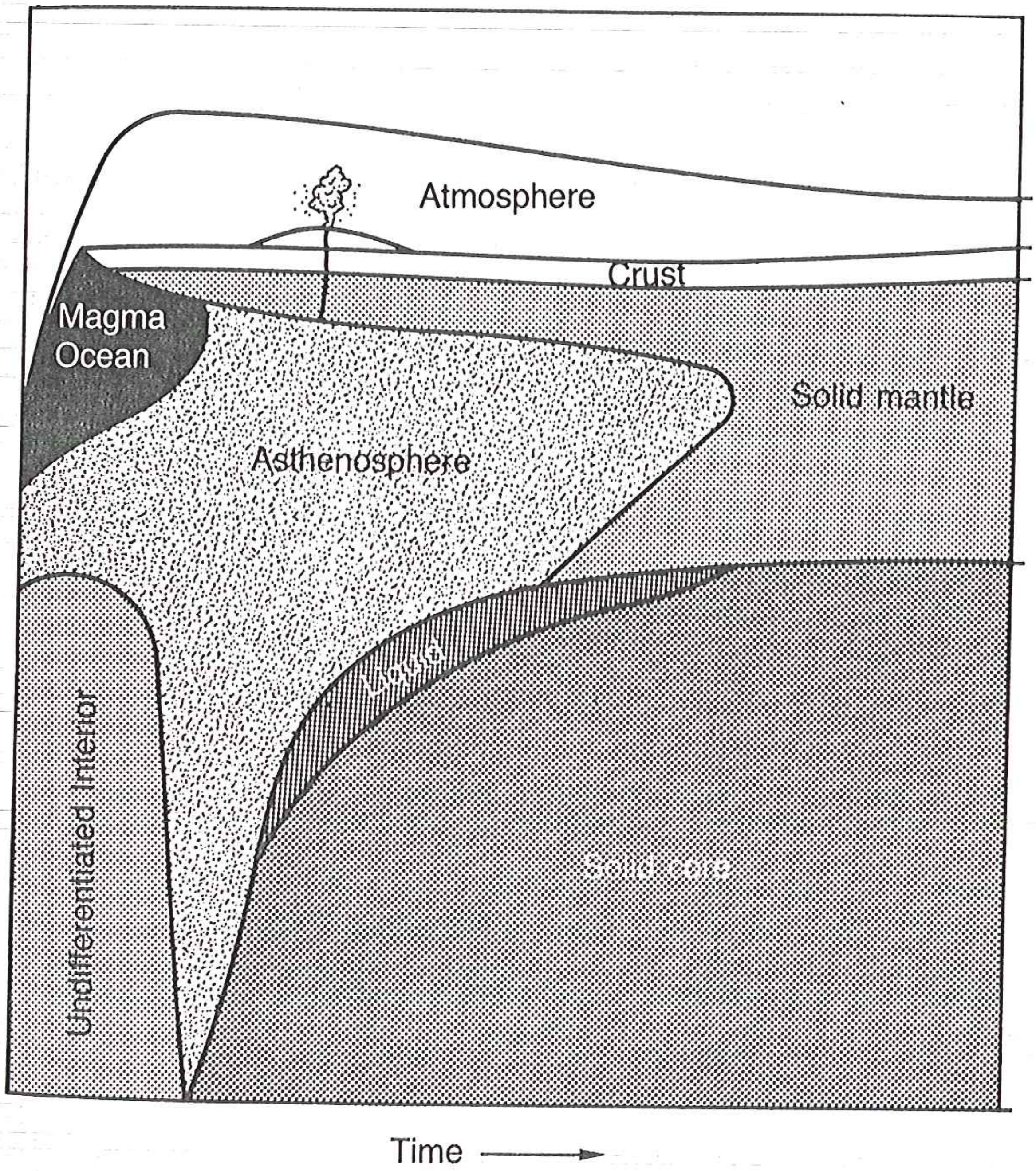


Figure 2.12

The thermal evolution of a terrestrial planet shows the changing temperature inside the planet. The time scale is relative. (Compare this diagram to those in chapters 4, 5, 6, and 7, which include absolute time estimates.) The occurrences, timing, and relative importance of these processes are unique to each planet and are determined by the planet's composition, mass, heat budget, and other characteristics.